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ROCK MINERALS

Their Chemical and Physical Characters and their Determination in Thin Sections

BY

JOSEPH P. IDDINGS

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FIRST THOUSAND

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PREFACE.

The term Rock Minerals is sufficiently indefinite to permit of considerable latitude in the choice of minerals to be included by it. Besides those that constitute the mass of any rock there are the less abundant though common kinds, as well as occasional, exceptional, ones. In any case the mineral may be an original constituent of the rock or one that has been developed in it subsequent to its formation. Rock Minerals, therefore, embrace not only all primary minerals, but all those of secondary origin produced by any manner of alteration of previously existing minerals. Among such secondary minerals are some that are better known as fillings of cavities and veins in rocks than as rock constituents, such as the zeolites. These, however, also occur as replacements of primary crystals within the body of rocks, and so constitute rock minerals in a narrower sense. The term becomes somewhat more comprehensive when it is applied to minerals formed in pegmatite veins, which are undoubtedly rocks of intrusive, igneous, origin, for there are many uncommon minerals well developed in such veins that are not known to crystallize within the main mass of larger rock bodies. However, it is customary to exclude certain classes of veins of minerals, such as ore veins, from the category of rocks, though their mode of formation in some instances is the same as that of many kinds of secondary rock minerals, and their study by petrographical methods in thin sections has been undertaken more or less systematically by several investigators. The inclusion of such vein minerals within the field of the petrographer would place almost the whole range of mineralogy before him and cause a distinction between the petrographer and mineralogist to consist, as it virtually does at present, in the objects and methods of research rather than in the materials investigated.

The study of rocks and their mineral components involves so

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many kinds of investigation, chemical, physical, mineralogical, and geological, that no petrologist is likely to follow all of them to their ultimate limit, but must content himself with some special branch of the subject, leaving to others the work in other branches. Thus, chemical investigations, to be of permanent value, must be carried on by one who is a skilled analyst; and the same is equally true of the physical, whether it concerns the optical or other physical characters of crystals or the chemicophysical problems involved in their crystallization. There is also a large field of work in the crystallography of minerals; while the geological study of the modes of occurrence and relationships and the probable history of rocks furnish ample opportunities for extended research to those especially fitted to pursue them.

The student beginning the subject of petrology needs at least an introductory knowledge of the branches of science that underlie mineralogy in order to apply certain of the principles to the study of rocks. This knowledge he is expected to have acquired in courses in chemistry, physics, mineralogy, and geology, but the broadness of these subjects makes it advisable to call attention to those particular principles that are immediately applicable to the study in hand. This has been put in the form of a review of some elementary principles in chemistry affecting an understanding of the composition of minerals; the same has been done with the principles involved in the use of optical methods for determining minerals in thin sections, and those relating to other physical features, particularly the theories concerning molecular structure and crystal form. Owing to the special use of thin sections in the investigation of rocks and to the employment of polarized light in their microscopical study, it is necessary to elaborate the review of the optical principles and to describe at considerable length the interference phenomena that become diagnostic characters of the rock minerals. The second part of the book contains descriptions of the better known rock minerals adapted to their study and identification in rocks, emphasis having been placed on their chemical composition as of fundamental petrological importance.

In the construction of the book I have availed myself of the data and material so ably presented to the student in the works of Groth, Dana, Rosenbusch, Hintze, Lévy and Lacroix, and of other mineralogists and petrographers. To Professor Groth I am indebted largely for the method of presentation of the physical characteristics of the minerals, which will be easily recognized by any one familiar

with his "Physikalische Krystallographie" and his "Einleitung in die chemische Krystallographie." From Professor Dana's "System of Mineralogy" has been taken much of the data concerning the chemical and physical properties of the minerals found in the descriptive part of the book, and I am under special obligation to him for his generous permission to use such illustrations from his book as were considered desirable in this one. The influence of Professors Rosenbusch and Wülfing's "Mikroskopische Physiographie der Mineralien und Gesteine" will be seen throughout the book, but no attempt has been made to attain to the completeness of the work of these writers. The student wishing to carry the study beyond the limits of this book will find in the fourth edition of the work just named a great amount of information on all phases of the subject. The bibliography of the subject is to be reached through that source. No attempt has been made to introduce it into this book, for the student who wishes to make use of the bibliography must have at his command an adequate library and a knowledge of foreign languages, and he will find that his best source of information is to be found in the work just mentioned. From the writings of Professors Lévy and Lacroix, especially "Les Minéraux des Roches," I have taken much relating to the optical characteristics of minerals, and have introduced the very beautiful and useful plate exhibiting the birefringence of minerals. I am also indebted to other friends who have aided the work by suggestions and additions, especially to Professor Julius Stieglitz for suggestions relating to the chemical principles.

It is with profound sadness and regret that my obligations to Samuel L. Penfield, late professor of mineralogy in the Sheffield Scientific School of Yale University, my classmate, colleague, and master in the realm of mineralogy, for frequent advice and constant inspiration, can not be acknowledged in person, but by reason of his untimely death must find expression in a dedication of this work to the memory of one who by his clear insight, honest enthusiasm, and singleness of purpose has accomplished so much for the advancement of the science of mineralogy.

JOSEPH P. IDDINGS.

CHICAGO, Oct. 2, 1906.

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ROCK MINERALS.

PART I.

GENERAL PRINCIPLES AND METHODS OF RESEARCH.

CHAPTER I.

CHEMICAL PRINCIPLES AND CHARACTERS.

Introduction.—The most fundamental character of a mineral is its composition, that is, its elemental constitution, involving the chemical elements that enter into its substance, their quantity, and their arrangement, or the structure of its molecule.

The determination of the kinds of elements present in a mineral may be accomplished by the incomplete methods of qualitative analysis. And in cases where a knowledge of the simple fact of the presence or absence of particular elements, taken in connection with characteristic physical features, serves to identify a mineral, this information may be sufficient for the purpose of the petrographer.

The determination of the quantity of the elements present in a mineral becomes necessary in many cases where the mineral belongs to an isomorphous series with variable proportions of certain elements and where the determinable physical characters are not distinctive of the precise chemical composition. In such cases the exact quantity of the elements present is to be obtained by means of quantitative chemical analysis.

The determination of the structure of the mineral molecule at present lies beyond the range of laboratory research, and is still within the realm of speculation and conjecture. By analogy with

certain organic compounds a possible structure of the molecules of some minerals has been suggested.

It is essential that the petrographer have a definite conception of the chemical principles involved in an understanding of the composition of the rock-making minerals, as well as of those relating to their formation and decomposition or alteration. Such conceptions traverse a wide field of physical chemistry, and become integral parts of the science of petrology. The formation and transformation of the rock minerals are so much a part of the problems of the origin and metamorphism of the rocks that the chemical principles involved in them will be discussed in immediate connection with the discussion of the rocks themselves. Those principles only which are involved in an understanding of the composition of the minerals will be reviewed briefly in this place. A thorough treatment of them must be sought in standard works on chemistry and mineralogy.

Chemical Elements.—The number of elements recognized at present in chemistry is about 80, a list of which is given in the table on the opposite page. Of these only a few occur in appreciable amounts in the rock-making minerals. Eight are common in considerable amounts and together form 99 hundredths of the solid surface portion of the earth as estimated by F. W. Clarke. They are: oxygen, silicon, aluminium, iron, calcium, magnesium, sodium, and potassium. The following are present in some of the commoner rock minerals in notable amounts: carbon, hydrogen, titanium, phosphorus, manganese, sulphur, chlorine, fluorine, lithium, boron, beryllium, zirconium; while other elements are present often in considerable amounts in the rarer minerals or are found in traces in the commoner ones. Such are: vanadium, nickel, cobalt, cerium, didymium, yttrium, zinc, tin.

Still others are found in very small traces in some rock minerals, or in certain cases as essential components of minerals whose occurrence in rocks is exceptional, or that belong properly to vein formations or to ore deposits. These are: gold, silver, copper, antimony, arsenic, bismuth, uranium. With the exception of gold, these have been found in very small traces in pyroxenes, hornblendes, biotites, and olivines in igneous rocks. In fact exhaustive analyses of all forms of rocks would probably show that all of the elements are to be found in them, though never all in any one body of rock.

Atom, molecule.—An *atom* is assumed to be an indivisible particle of an element, having a definite mass for each kind of element. One or more atoms are capable of combining with one or more atoms

of other elements to form a chemical compound. It is the smallest mass of any element that can take part in a chemical reaction. A symbol consisting of one or two letters, as H or Si, is used to represent the name of an element, and also to represent one atom of the element and may also represent its atomic weight.

CHEMICAL ELEMENTS AND THEIR ATOMIC WEIGHTS.[1]

Aluminium	Al	27.1	Neon	Ne	20.0
Antimony	Sb	120.0	Nickel	Ni	58.7
Argon	A	40.0?	Niobium = Columbium	Nb	94.0
Arsenic	As	75.0	Nitrogen	N	14.04
Barium	Ba	137.4	Osmium	Os	191.0
Beryllium = Glucinum	Be	9.1	Oxygen	O	16.0
Bismuth	Bi	208.3	Palladium	Pd	106.5
Boron	B	11.0	Phosphorus	P	31.0
Bromine	Br	79.95	Platinum	Pt	195.0
Cadmium	Cd	112.35	Potassium	K	39.14
Cæsium	Cs	132.9	Praseodymium	Pr	140.45
Calcium	Ca	40.1	[2] Radium	Ra	225.0
Carbon	C	12.0	Rhodium	Rh	103.0
Cerium	Ce	140.0	Rubidium	Rb	85.4
Chlorine	Cl	35.45	Ruthenium	Ru	101.7
Chromium	Cr	52.1	Samarium	Sa	150.0
Cobalt	Co	59.0	Scandium	Sc	44.0
Columbium = Niobium	Nb	94.0	Selenium	Se	79.2
Copper	Cu	63.6	Silicon	Si	28.4
Erbium	Er	166.0	Silver	Ag	107.93
Fluorine	F	19.0	Sodium	Na	23.05
Gallium	Ga	70.0	Strontium	Sr	87.68
Germanium	Ge	72.5	Sulphur	S	32.06
Glucinum = Beryllium	Gl	9.1	Tantalum	Ta	183.0
Gold	Au	197.2	Tellurium	Te	127.5
Helium	He	4.0	Terbium	Tr	160.0
Hydrogen	H	1.01	Thallium	Tl	204.1
Indium	In	114.0	Thorium	Th	233.0
Iodine	I	126.85	Thulium	Tu	170.0?
Iridium	Ir	193.0	Tin	Sn	119.0
Iron	Fe	56.0	Titanium	Ti	48.15
Krypton	Kr	81.8	Tungsten	W	184.0
Lanthanum	La	138.5	Uranium	U	240.0
Lead	Pb	206.9	Vanadium	V	51.4
Lithium	Li	7.03	Xenon	X	128.0
Magnesium	Mg	24.35	Ytterbium	Yt	173.0
Manganese	Mn	55.0	Yttrium	Y	89.0
Mercury	Hg	200.0	Zinc	Zn	65.4
Molybdenum	Mo	96.0	Zirconium	Zr	90.5
Neodymium	Nd	143.6			

A *molecule* is assumed to be the least part of an element or of a compound that possesses the properties of the free element or compound, or that can exist in a free state. In most cases a gas molecule consists of two or more atoms. Thus it is found that a molecule of hydrogen gas must consist of two atoms of hydrogen, H_2; a molecule of

[1] Taken from "The Elements of Physical Chemistry," by H. C. Jones.

[2] Inserted in table copied.

oxygen must consist of two atoms of oxygen, O_2. A gas molecule of hydrogen chloride consists of one atom of hydrogen and one of chlorine, HCl. A gas molecule of water consists of two atoms of hydrogen and one of oxygen, H_2O. But the gas molecules of mercury, cadmium, zinc, potassium, and sodium consist of one atom each. The same is true for the gas molecules of argon, helium, neon, krypton, and xenon. It is known that the gas molecules of some elements consist of different numbers of atoms under different conditions of temperature and pressure. Thus iodine gas molecules consist of two atoms at moderate temperatures, but break up into monatomic molecules at high temperatures. The gas molecule of phosphorus consists of four atoms at temperatures below 1600° C.; above this it consists of two atoms. The gas molecule of sulphur at 500° C. contains six atoms, at 1000° C. it contains two atoms.

Upon passing into the liquid state there appears to be an increase in the number of atoms in the molecule, so that a liquid molecule of sulphur is some multiple of six atoms, but the number of atoms in liquid molecules in general cannot be determined. In the case of water Ramsay and Shields concluded that the liquid molecule consists of four gas molecules, that is, $(H_2O)_4$ or H_8O_4, and this view appears to be confirmed by others.

The crystal molecule is probably composed of some multiple of the number of atoms in the liquid molecule, but there is no method known by which the relative numbers of atoms in these two kinds of molecules of a substance can be exactly determined.

In size a molecule is considered to be somewhere between the limits of 1/20,000,000 mm. and 1/100,000,000 mm. in diameter.

When the molecular weight of a substance cannot be determined, so that the number of atoms of each element entering into it is not known, it is customary to designate the least number of atoms that will express the proportions of the constituents as the molecule. Thus $KAlSi_3O_8$ expresses the proportion of potassium, aluminium, silicon, and oxygen in orthoclase feldspar, but it is not to be supposed that a molecule of orthoclase contains but one atom of potassium, one of aluminium, three of silicon, and eight of oxygen; its molecule may be $(KAlSi_3O_8)x$. It is customary in mineralogy to call this simplest expression of the chemical composition of a mineral the *chemical molecule* in distinction to the physical molecule. But it may be pointed out that this is misleading, for it is necessary in treating of the chemical properties of compounds to indicate the number of atoms of each element present in the molecule when known, since the

chemical behavior of similarly proportioned compounds having different molecular weights, that is, different numbers of the same atoms, is different. A very simple example is the difference in chemical properties between oxygen, O_2, and ozone, O_3.

Molecular and Atomic Weights.—On the basis of Avogadro's law that equal volumes of all gases at the same temperature and pressure contain an equal number of molecules it is possible to determine the relative molecular masses or weights of gases, which may be referred to that of the lightest, hydrogen, as a standard. The hypothesis of van't Hoff that the osmotic pressure in dilute solutions is the same as gas-pressure, and his conception of isomorphous or "mixed" crystals as solid solutions, have extended the possibilities of determining in certain cases the molecular weights of chemical compounds in a liquid and also in a solid state.

From these determinations and from a consideration of the possible number of ultimate parts or atoms of an element that may be present in the gas molecule of its compounds the relative mass, or the combining weight of an atom, may be calculated. These *atomic weights* are generally referred to the mass of an atom of hydrogen, which is taken as 1., when that of an atom of oxygen is 15.88; or they are referred to oxygen taken as 16., when the mass of an atom of hydrogen becomes 1.0075. In the Table of Elements oxygen is taken as the standard at 16. But in ordinary petrographical usage the atomic weights are taken in whole numbers without decimals, so that the distinction between the standards just mentioned does not affect the calculations.

Since in general the mass or size of molecules of the rock-making minerals is indeterminable, it is not possible to reckon the actual molecular weight of any of these compounds. However the weight of the so-called chemical molecule may be calculated from the atomic weights of its component elements. This is the sum of the weights of the constituent atoms, and is called the *molecular weight* of the compound. Thus the molecular weight of quartz, SiO_2, is $28+16\times2=60$; that of orthoclase, $KAlSi_3O_8$, is $39+27+28\times3+16\times8=278$.

Valence.—The elements combine with one another in various proportions as to numbers of atoms that are capable of forming definite compounds. Thus hydrogen and oxygen combine in the proportions of two atoms of hydrogen to one of oxygen to form water $(H_2O)_4$. Calcium and oxygen combine in the proportion of one atom of each to form lime, $(CaO)_m$. Two atoms of iron combine with three

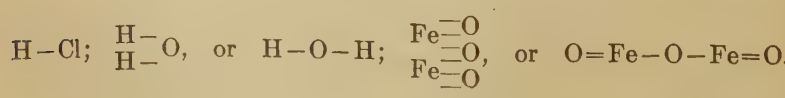
of oxygen to form ferric oxide (Fe_2O_3). One atom of silicon combines with two of oxygen in silica (SiO_2). An atom of oxygen having a given mass, it is evident that the elements just mentioned have the ability to attach themselves to different amounts of oxygen. This ability to combine with one, two, or more atoms of a given element is termed the combining strength or *valence* of an element. Hydrogen or an element of the same valence is taken as the standard of comparison. An element that will combine with one atom of hydrogen is said to be univalent; one combining with two atoms of hydrogen is bivalent; and so on.

Some elements are capable of combining in more than one proportion with other elements. They appear to possess more than one valence. Examples of such elements will be given below. The following list is a partial statement of the valence of the commoner elements. It is headed by the rare elements which are not known in chemical combination and are said to have no valence. Those that are known to have more than one valence are placed in parentheses.

Zero valent:	A, He.
Univalent:	H, (Cl, Br, I, F); Li, Na, K, Ag, (Cu, Au, Hg).
Bivalent:	(O, S, Se, Te); Be, Mg, Ca, Sr, Ba, Zn, Cd, (Hg), (Fe, Mn, Pb, Cu, Co, Ni), (C), (Pt, Sn).
Trivalent:	B, (Au); Al, (Fe, Mn, Cr, Mo, W), Y, Di, (N, P, V, As, Sb, Bi).
Tetravalent:	(C), Si, Ti, Zr, (Sn), Ce, La, (Pb), (U), (Mn).
Pentavalent:	(N, P, V, As, Sb, Bi), Nb, Ta.
Hexavalent:	(S, Se, Te), (Cr), (Mo, W), (U).
Heptavalent:	(Cl, Br, I), (Mn).
Octavalent:	Os.

Examples of the apparent different valency of some of the elements are: FeS, Fe_2O_3, FeS_2; Cu_2O, CuO; Sb_2O_3, Sb_2O_5; HCl, Cl_2O_7.

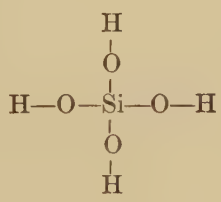
The valence of an element may be expressed by supposing it to possess a number of bonds by which it may be united with another element; univalent elements possessing one bond; bivalent, two bonds; and so on. This may be represented in the following manner:



Formulæ.—A statement of the proportionate number of atoms of the elements entering a compound may be expressed by combining in a formula the symbols for the elements and numbers corresponding to the number of atoms of each. When given in terms of the least number of atoms that will express the proportions of the elements, as $CaAl_2Si_2O_8$ for anorthite, it is called an *empirical* formula, since it represents simply the results of quantitative analysis.

Other forms of expression are often used indicating by the arrangement of the atoms the nature of the compound, as $CaAl_2(SiO_4)_2$, indicating that the compound is to be considered an orthosilicate of calcium and aluminium. The expression is derived from that of orthosilicic acid, H_4SiO_4. It may also be expressed as though it were composed of oxides, as CaO, Al_2O_3, $2SiO_2$. This is called a *dualistic* formula, and while misleading in its suggestion that the compound is made up of three oxides, lime, alumina, and silica, it is convenient for comparison with the statement of the analysis of the mineral, which is given in the form of oxides in most instances. Because of greater convenience in calculating the mineral composition of rocks from the chemical analyses of rocks, and *vice versa*, the dualistic formulæ will be frequently employed in describing the rock-making minerals.

Formulæ that suggest a possible arrangement of the atoms in a chemical molecule by placing the symbols for the atoms in various positions with bonds of affinity connecting them are called *structural* or *graphic* formulæ. Thus orthosilicic acid, $Si(CH)_4$, may be represented as



The difficulty of investigating the chemical character of the silicate compounds has prevented such formulæ from becoming sufficiently well established to be of more than speculative interest. They have been discussed by F. W. Clarke [1] in connection with the silicates.

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[1] The Constitution of the Silicates, Bull. 125, U. S. Geological Survey. Washington, 1895.

Calculation of Formulæ from Chemical Analyses.—Since the total mass of a compound is equal to the sum of the masses of its component elements, it follows that the ratio of the total mass of the compound to the molecular weight of the compound is the same as that of the total mass of each component element to the weight of the atoms of each element present in the molecule. Consequently it is possible to find the relative number of atoms of the element in the molecule by dividing the relative masses of each, their percentage weights, by the atomic weight of each element.

If the percentage weights in an analysis are expressed for oxides of the elements, these are to be divided by the molecular weight of each oxide. The resulting quotients will be the proportions of the oxides in the dualistic formula, from which the empirical formula is readily derived.

	Per cent.		Mol. wt.		Mol. ratio.
SiO_2	68.7	÷	60	=	1.145=6
Al_2O_3	19.5	÷	102	=	.191=1
Na_2O	11.8	÷	62	=	.190=1
	100.0				

From this we find $Na_2O \cdot Al_2O_3 \cdot 6SiO_2$, or $Na_2Al_2Si_6O_{16} = NaAlSi_3O_8$, the empirical formula for albite.

Electrical Behavior of the Elements.—From the behavior of a solution of a salt, acid, or base in water toward the passage of an electric current it has been concluded that such a solution contains the salt, acid, or base in a state of dissociation into two or more parts, each fragment being charged with positive or negative electricity, the metal atoms forming positively charged particles or *ions*, the remaining atoms of the molecule forming negatively charged fragments or *ions*. For example, sodium chloride seems to be decomposed by water into (+) Na and (−) Cl ions; sodium sulphate into (+) 2 Na and (−) SO_4 ions. Now when an electric current is passed through such solutions all the positively charged particles are attracted by the negative electrode and migrate toward it, all the negative ions migrating for a similar reason to the positive electrode, thus establishing the electric current. As the ions touch the electrodes their electricity is discharged and chemical decomposition occurs consequently at the electrodes. This hypothesis is supported by the determination of the molecular weights of such electrolytic compounds in solutions, on

the basis of van't Hoff's extension of Avogadro's Law.[1] When water is electrolyzed the hydrogen behaves as if it were positively charged, the oxygen as though negatively charged. A certain element may become positive when compared with one element and negative when compared with another. The electrical behavior is not necessarily a fixed characteristic of an element.

Acids.—Compounds of negative elements, F, Cl, C, S, Si, etc., with hydrogen or hydroxyl (HO), in which the hydrogen may be replaced by other positive elements, are called *acids*. Common acids are:

HCl, hydrochloric acid	H−Cl
H_2CO_3, carbonic acid	$(HO)_2=CO$
H_2SO_4, sulphuric acid	$(HO)_2=SO_2$
H_2SiO_3, metasilicic acid	$(HO)_2=SiO$
H_4SiO_4, orthosilicic acid	$(HO)_4\equiv Si$
$H_4Si_3O_8$, polysilicic acid	$(HO)_4\equiv Si_3O_4$

Some elements are capable of forming more than one acid, as illustrated by the three silicic acids just given. Acids with one atom of hydrogen or one hydroxyl radical are called *monobasic*, as HCl. Those with two atoms of hydrogen or two hydroxyls are *dibasic*, as H_2CO_3, H_2SiO_3. Those like H_4SiO_4 are *tetrabasic*.

Bases.—Compounds of positive elements with hydroxyl (OH), or of the oxides of such elements with water, as $K_2O+H_2O=2K(OH)$ form *bases*. Commoner examples are

K(OH), potassium hydrate	(OH)−K
Na(OH), sodium hydrate	(OH)−Na
$Ca(OH)_2$, calcium hydrate	$(OH)_2=Ca$
$Fe(OH)_2$, ferrous hydrate	$(OH)_2=Fe$
$Fe(OH)_3$, ferric hydrate	$(OH)_3\equiv Fe$
$Al(OH)_3$, aluminium hydrate	$(OH)_3\equiv Al$

It is possible also to combine a basic radical, as (AlO), with a hydroxyl to form a base; for example,

(AlO)(OH); (FeO)(OH).

Salts.—A compound which may be formed by combining a base and an acid is called a *salt*. $Ca(OH)_2+H_2CO_3=CaCO_3+2H_2O$. It may be described as an acid in which the atoms of hydrogen are

[1] See further on this subject in S. Arrhenius, Text-book of Electrochemistry; J. Walker, Introduction to Physical Chemistry; H. C. Jones, Elements of Physical Chemistry.

replaced by a positive element, or radical. The following are salts of silicic acids:

H_2SiO_3: $MgSiO_3$, enstatite; $CaSiO_3$, wollastonite; $NaAl(SiO_3)_2$, jadeite.
H_4SiO_4: Mg_2SiO_4, forsterite; $CaAl_2(SiO_4)_2$, anorthite.
$H_4Si_3O_8$: $NaAlSi_3O_8$, albite.

Normal, Acid, and Basic Salts.—A *normal* or *neutral* salt is one in which the acid is completely neutralized by the base, that is, in which all of the hydrogen atoms are replaced by other positive elements or radicals. Thus Na_2CO_3 is normal sodium carbonate, all of the hydrogen in H_2CO_3 being replaced by sodium. $Al(AlF_2)SiO_4$ is normal aluminium fluosilicate, the radical having one aluminium bond to combine with.

An *acid* salt is one in which part of the hydrogen of the acid remains. The acid is not completely neutralized by the base. Thus $HNaCO_3$ is acid sodium carbonate. The formula may be written $H_2CO_3 \cdot Na_2CO_3$, showing that the compound may be considered as made up of equal parts of normal sodium carbonate and carbonic acid. $H_2KAl_3(SiO_4)_3$ (muscovite) is acid orthosilicate of potassium and aluminium.

A *basic* salt is one in which the base is not completely satisfied by the acid. $Mg_2(OH)_2SO_4$ is basic sulphate of magnesium, and may be written $Mg(OH)_2 \cdot MgSO_4$. Zoisite is basic orthosilicate of calcium and aluminium, $Ca_2Al_3(OH)(SiO_4)_3$.

Radicals.—When a certain group of atoms occurs in the molecules of a number of different compounds, or appears to remain intact in a series of transformations of a compound entering into the molecules of new compounds formed, the group is often termed a *radical*. Thus in the bases there is the radical (OH); in sulphuric acid the radical (SO_4); in orthosilicic acid the radical (SiO_4). Since the radicals are parts of molecules, they are supposed to have uncombined or free valencies; thus OH is univalent, as in H−OH, K−OH; SO_4 is bivalent, as in $H_2{=}SO_4$, $Mg{=}SO_4$; SiO_4 is tetravalent, as in $H_4{\equiv}SiO_4$, $Mg_2{\equiv}SiO_4$. But it is to be noted that radicals are not known to exist in an uncombined state.

Water of Crystallization. — Upon heating hydroxides and basic or acid salts water is given off, usually at a high temperature. This water is not considered to be present in the compound as water, but to be intimately combined with the other constituents. There are

definite compounds that yield water readily upon moderate heating, and it is customary to call this *water of crystallization* and consider it to exist as water in the compound. Its presence is expressed in the formula by the addition of a certain number of molecules of H_2O: $NaAl(SiO_3)_2+H_2O$ (analcite), $Ca(AlOH)_2$ $(SiO_3)_3+2H_2O$ (scolecite). It is probable, however, that these atoms of hydrogen and oxygen are parts of the chemical molecule as the other constituent atoms are, but by reason of the structure of the molecule have a weaker connection, that is, are so placed as to be readily separated from the others upon an increase of temperature.

Chemical Similarity among Groups of Elements.

Periodic Law of Mendeléeff and Lothar Meyer.—A comparison of the properties of the chemical elements shows that there are groups of elements having numerous points of resemblance in chemical behavior and physical properties, and in the characters of the compounds into which they enter. These relationships have been particularly investigated independently by Mendeléeff and Lothar Meyer, who arrived at the conclusion that the properties of the elements are periodic functions of their atomic weights. The significance of this will appear upon inspection of the table of elements arranged by Mendeléeff (page 12). The importance of the law for the petrographer is in its application to the problem of isomorphous compounds, as well as of morphotropism, to be discussed later on.

When the elements are arranged according to their atomic weights, beginning with the lightest, it is found that, with some exceptions, there is a succession of groups or of series of elements having certain resemblances and certain differences. Referring to the table it will be seen that, beginning at the upper left-hand corner, the elements are arranged in ten horizontal series according to increasing atomic weights. They are further arranged in nine vertical columns, and within each column there is a left- and right-handed arrangement. A few of the more prominent characteristics brought into order by this system will be pointed out.

Valence.—Elements occurring in the same vertical column, or " group," have the same maximum valence toward oxygen or chlorine. But it should be remembered that some elements have more than one valence. So that the system does not indicate all of the relationships. The first column, or zero-group, contains the new elements known only as monatomic gases, apparently without power of combination.

TABLE OF ELEMENTS ARRANGED ACCORDING TO THEIR ATOMIC WEIGHTS.

SERIES.	GROUP 0. R.	GROUP I. — R_2O.	GROUP II. — RO.	GROUP III. — R_2O_3.	GROUP IV. RH_4 RO_2.	GROUP V. RH_3 R_2O_5.	GROUP VI. RH_2 RO_3.	GROUP VII. RH R_2O_7.	GROUP VIII. — RO_4.
1		H = 1							
2	He = 4	Li = 7	Be = 9	B = 11	C = 12	N = 14	O = 16	F = 19	
3	Ne = 20	Na = 23	Mg = 24	Al = 27	Si = 28	P = 31	S = 32	Cl = 35	
4	A = 40?	K = 39	Ca = 40	Sc = 44	Ti = 48	V = 51	Cr = 52	Mn = 55	Fe = 56, Co = 59, Ni = 58.7, Cu = 63.6
5		Cu = 63.6	Zn = 65	Ga = 70	Ge = 72.5	As = 75	Se = 79	Br = 80	
6	Kr = 81.8	Rb = 85	Sr = 88	Y = 89	Zr = 90.5	Nb = 94	Mo = 96	—	Ru = 102, Rh = 103, Pd = 106, Ag = 108
7		Ag = 108	Cd = 112	In = 114	Sn = 119	Sb = 120	Te = 127.5	I = 127	
8	X = 128	Cs = 133	Ba = 137	La = 139	(Ce, etc., = 140 to 178)	Ta = 183	W = 184	—	Os = 191, Ir = 193, Pt = 195, Au = 197
9		Au = 197	Hg = 200	Tl = 204	Pb = 207	Bi = 208	—	—	
10		—	Ra = 225	—	Th = 233	—	U = 238.5	—	

The univalent elements fall in Group I, the place of hydrogen not being clearly established. Group II contains bivalent elements, but some that are bivalent and have a higher valence as well fall elsewhere: Fe, Ni, Co. Similar observations may be made in the other groups.

Considering the ability of the elements to combine with oxygen, it is seen that in Series I the valence increases regularly from Group I to Group VIII, in which osmium is known to combine with four oxygen atoms. The same is true of the ability of the elements to combine with chlorine. There is a regular increase from Group I to Group VI, WCl_6 being known. With respect to the valence of the elements towards hydrogen the case is different and there is a regular decrease from Group IV to Group VII.

Basic and Acid Properties.—It will be noted that of the elements in each horizontal series that with the lowest atomic weight and the lowest valence with respect to oxygen has the strongest basic character, while that with the highest atomic weight has the strongest acidic character. Moreover these characters grade from one extreme to the other, some of the elements in the middle groups showing variable basic or acid characters depending upon conditions.

Chemical Similarities.—The elements in the vertical columns or groups are so arranged that those in alternate series are vertically in line, making two subgroups in each group. Those occurring in one subgroup are more alike in their chemical characters than they are like the elements in the other subgroup. They are capable of forming compounds which are commonly closely alike physically and are often isomorphous. Thus lithium, potassium, rubidium, cæsium resemble one another closely chemically, more so than they do sodium, copper, silver, and gold. The last three of these form isomorphous minerals. Lithium and potassium appear in isomorphous crystals, as in mica. Potassium and sodium are closely related and are also capable of forming isomorphous salts, as in feldspar. But there are numerous instances in which chemically analogous salts of these elements crystallize quite differently. Thus $KAl(SiO_3)_2$, leucite, and $NaAl(SiO_3)_2$, jadeite; but $LiAl(SiO_3)_2$, spodumene, is like jadeite in crystallization, Moreover $NaAl(SiO_3)_2+H_2O$, analcite, is isomorphous with leucite.

In Group II calcium, strontium, and barium resemble one another closely and form similar chemical compounds; also magnesium, zinc, and cadmium. But there is a strong resemblance between calcium and magnesium, and bivalent iron and manganese are very intimately related to magnesium, forming numerous isomorphous silicate salts. Bivalent lead is closely related to barium and strontium. So there

are very similar carbonates of calcium, strontium, barium, and lead; another series of carbonates of calcium, magnesium, iron, manganese, and zinc.

In Group III aluminium is closely related to trivalent iron, also trivalent manganese and chromium. These elements frequently form similar chemical compounds; for example, the spinels and garnets. Most of the elements in this group are rare.

In Group IV silicon, titanium, and zirconium have somewhat similar properties and are capable of replacing one another to some extent in the rock-making minerals.

The elements of Group V enter but slightly into the composition of the rock minerals, except phosphorus in apatite. With phosphorus are closely related arsenic and vanadium.

Of the elements in Group VI oxygen is the most common component of the rock minerals, and appears to play a unique rôle chemically. The close chemical relationship between sulphur, selenium, and tellurium is well known.

In Group VII the chemical similarity of chlorine, bromine, and iodine is shown in numerous isomorphous salts.

In Group VIII iron, cobalt, and nickel are very similar and form isomorphous compounds with suphur and arsenic. Platinum is closely related to iron and enters isomorphous salts with iron and arsenic. Moreover iron, cobalt, and nickel are intimately associated in meteorites, while platinum is intimately associated with iridium and osmium.

The physical properties of the elements are closely in accord with the system of grouping presented in the table. There are numerous imperfections and apparent incongruities in the system, but it clearly indicates some fundamental periodic relationship between the atomic mass and the chemical and physical properties, probably more complex than can be expressed by the simple arrangement in two directions in the table.

Isomorphism.—Compounds having analogous chemical compositions and crystallizing in the same forms are said to be *isomorphous*. But the analogy in chemical composition may range from close resemblance, such as that between $FeSiO_3$ and $MgSiO_3$, to rather remote analogy, as between $CaSiO_3$ and $NaFe(SiO_3)_2$, or between $NaAlSi_3O_8$ and $CaAl_2Si_2O_8$; and the likeness in form may vary from identity, as in the case of crystals in the isometric system, such as spinels, to close relationship, as that of two monoclinic forms with like symmetry and almost the same axial ratio—the monoclinic pyroxenes. How-

ever, it may include crystals not having the same degree of symmetry though closely related, as the scalenohedral class of the trigonal system (calcite) and the trirhombohedral class of the same system (dolomite). Moreover it is possible for compounds to have identical forms without possessing similar compositions, as is the case with galena and fluorite, and such are not considered to be isomorphous.

The definition of isomorphism clearly is not complete as just stated. It is necessary to add the condition that isomorphous compounds are capable of crystallizing together in all proportions to form a chemically and physically homogeneous crystal. Thus Fe_2SiO_4 (fayalite) and Mg_2SiO_4 (forsterite) each form crystals in the bipyramidal class of the orthorhombic system, which differ slightly in axial ratios: $a:b:c=0.4584:1:0.5793$ (fayalite); $a:b:c=0.4648:1:0.5857$ (forsterite). They crystallize together in all proportions in crystals (olivine) resembling those of the simple compounds, and the physical properties of the series of mixed compounds form continuous series between those of the simple compounds, so far as known. This is true in general of isomorphous mixtures.

The serial change in the physical properties in an isomorphous series that appears in a serial variation in crystal form, that is, a variation in the angles between homologous faces or planes accompanying a variation in the chemical composition, is called *morphotropism*. Strictly speaking, absolute isomorphism only exists in compounds crystallizing in the isometric system. In all other cases there is more or less evident morphotropism.

The isomorphous mixture is called a *mixed salt*, and the resulting homogeneous crystal a *mixed crystal*. The formula for the example just given is $(Mg,Fe)_2SiO_4$, which expresses the fact that Mg and Fe are present in any proportion; the use of the comma between Mg and Fe indicating an indefinite proportion between them, or that one partly replaces the other in the molecule.

The relations brought out in the arrangement of the elements according to the periodic system show what compounds may be expected to be isomorphous, though the full expectation expressed in the law of Mitscherlich, that the crystal form of compounds having analogous chemical compositions is the same, is not realized in all cases. However, the instances are so numerous that the importance of the relationship is fundamental, and the student will find it an assistance to the memory in recollecting the composition of minerals belonging to isomorphous groups. Examples from the rock minerals are the following:

The elements Li, Na, K are common. It will be noticed in the table that in some respects Li and K are more closely related than Na and K, and that Na and K occur in different subdivisions of Group I. Some of the isomorphous salts of these elements are:

Hexagonal	$LiAl(SiO_4)$, eucryptite	extremely rare.
	$NaAl(SiO_4)$, nephelite	common.
	$KAl(SiO_4)$, kaliophilite	extremely rare.

On the other hand these three elements form isomorphous salts, probably with closely similar chemical compositions, in the micas: lepidolite, paragonite, muscovite, of which the lithium-mica and potassium-mica are common, and the sodium-mica is rare.

Monoclinic	$LiAl(SiO_3)_2$, spodumene	common.
	$NaAl(SiO_3)_2$, jadeite	very rare.

But $KAl(SiO_3)_2$, leucite, crystallizes in the isometric system and is not isomorphous with the others.

Triclinic	$NaAlSi_3O_8$, albite	common.
	$KAlSi_3O_8$, microcline	common.

The independence of Na and K is shown by the numerous compounds into which Na enters without an isomorphous K equivalent. For example: the acmite molecule, $NaFe(SiO_3)_2$; the scapolite and zeolite series of minerals, in which Na_2 and Ca form isomorphous compounds.

With respect to the relative strengths of these three elements as positive elements or bases, in silicates, it appears that Li has the strongest affinity for silicon, being known to occur as a disilicate, $R_2Si_2O_5$, in petalite, $LiAl(Si_2O_5)_2$, the highest silicate known; while K occurs in small amounts in the disilicate, milarite, a rarer mineral. K and Na are both common as polysilicates, $R_4Si_3O_8$, in orthoclase and albite. But K is common as a metasilicate, $RSiO_3$, leucite, and Na is commoner as an orthosilicate, R_4SiO_4, nephelite. So that K appears to have a stronger affinity for silicon than Na. Their relative basic characters may be expressed as $Li > K > Na$.

The alkaline earths common in the rock minerals are Mg, Ca, and also Fe, which in the periodic system is remote from both Mg and Ca. There is a close relationship between Mg and Fe, and also Mn, not shown in the periodic system. It is to be remembered that Fe and

Mn have variable valence. It is bivalent Fe and Mn that are intimately related to Mg. It is to be noted that Mg and Ca belong to different subdivisions of Group II, and while they have some chemical resemblances they have well-known chemical differences which are well illustrated in the rock minerals. Sr and Ba are closely related to Ca, but are not common in rock minerals. Isomorphous salts of this group of elements are shown in the carbonates and silicates.

Trigonal:
- $CaCO_3$, calcite. — $(Ca,Mg)CO_3$, dolomite.
- $MgCO_3$, magnesite. — $(Ca,Mg,Fe)CO_3$, ankerite.
- $FeCO_3$, siderite.
- $MnCO_3$, rhodochrosite.
- $ZnCO_3$, smithsonite.

The carbonates of Ca, Sr, Ba, and Pb are isomorphous, orthorhombic, salts; so are also the sulphates of the same elements.

Isometric:
- $Ca_3Al_2(SiO_4)_3$, grossularite garnet.
- $Mg_3Al_2(SiO_4)_3$, pyrope "
- $Fe_3Al_2(SiO_4)_3$, almandite "
- $Mn_3Al_2(SiO_4)_3$, spessartite "

This group of minerals also illustrates the isomorphism of salts of Al, Fe, and Cr, as it also contains the compounds

Isometric:
- $Ca_3Fe_2(SiO_4)_3$, andradite garnet
- $Ca_3Cr_2(SiO_4)_3$, uvarovite. "

These compounds are capable of combining in any proportion to form homogeneous crystals.

Most other silicates of calcium and magnesium illustrate differences in the behavior of these elements, rather than strict isomorphism. Thus they both enter into pyroxenes, amphiboles, and into the olivine group in the rare mineral monticellite, but their difference of behavior in each case is noticeable.

In pyroxene MgFe silicate is orthorhombic, Ca silicate is monoclinic.

Orthorhombic:
- $MgSiO_3$, enstatite.
- $(Mg,Fe)SiO_3$, hypersthene.

Monoclinic...:
- $CaSiO_3$, wollastonite.
- $CaMg(SiO_3)_2$, diopside.
- $Ca(Mg,Fe)(SiO_3)_2$, hedenbergite.

But it may be that the orthorhombic character of enstatite and hypersthene is in fact a case of polysymmetry (page 67).

The mixture of $CaSiO_3$ and $MgSiO_3$ does not occur in all proportions, but Mg and Fe may vary indefinitely The same is true in the amphiboles and in the olivine group. In monticellite the composition is $Ca(Mg,Fe)SiO_4$. In pyroxene and in monticellite the ratio of $Ca:(Mg,Fe)=1:1$, while in the amphiboles, tremolite and actinolite, it is 1 : 3. These are examples of *molecular compounds*.

In many rock minerals calcium occurs without magnesium or iron, as in feldspars, scapolite, zeolites, etc.; and in others magnesium and iron occur without calcium, as in the olivines of igneous rocks, micas, spinels, chlorites, etc. In nearly all cases in which magnesium and iron occur together the proportions between them are indefinite, or rather they are not fixed for any given mineral. The physical independence of magnesium and iron is shown in the preponderant occurrence of bivalent iron in magnetite, ilmenite, and epidote. But it is known that magnesium is capable of entering these compounds isomorphously, and it is sometimes present in these minerals in very small amounts.

As to the relative strength of affinity of these alkaline earths for silicon it is to be noted that while calcium and magnesium form metasilicates—pyroxenes and amphiboles,—and both form orthosilicates—garnets,—there is no common calcium orthosilicate equivalent to the very common olivine compound. It would seem, as indicated in the periodic system, that calcium behaves as a stronger base than magnesium with respect to silicon. The calcium pyroxenes are more stable than the magnesian pyroxenes free from calcium. In the carbonates the magnesian salts appear to be more stable than the calcium carbonate.

The isomorphism of compounds containing Al, Fe, and Cr is well illustrated in numerous rock-making minerals. It has been already noted in the case of the garnets. It is pronounced in the spinels. Al and Fe have like crystal forms as oxides, corundum, and hematite, but do not form mixed crystals and are therefore not strictly isomorphous. These elements occur together in variable proportions in many ferro-magnesian minerals—pyroxenes, amphiboles, micas, epidote, etc.

Of Group IV, C, Si, Ti, and Zr are common in rock minerals, C and Si being the most abundant. But while silicon, titanium, and zirconium are found entering isomorphous compounds and replacing one another to some extent, the four elements mentioned do not commonly produce isomorphous salts, but are quite independent in their behavior; especially is this true of carbon and silicon in rock

minerals. The chemically analogous carbonates and silicates of Ca, Mg, Fe, Mn, are very different in crystal characters, one belonging to the calcite group, RCO_3, the other to the pyroxene group, $RSiO_3$. Similarly the few titanates and chemically analogous silicates are quite different in crystal forms. Compare $(Fe,Mg)TiO_3$, ilmenite, with $(Mg,Fe)SiO_3$, hypersthene; or $CaTiO_3$, perofskite, with $CaSiO_3$, wollastonite. It is to be noted in the case of the two titanates mentioned that Ca and (Fe,Mg) do not furnish isomorphous compounds, perofskite being isometric, and ilmenite trigonal. Titanium probably replaces silicon isomorphously in a number of ferromagnesian rock minerals, and zirconium undoubtedly plays the same rôle in such rare minerals as rosenbuschite, lovenite, and wöhlerite, which are related to the pyroxenes.

Dimorphism or Polymorphism.—The same compound may crystallize in two distinct classes of symmetry, when it is said to be *dimorphous*. When in three classes it is called *trimorphous*, or oftener *polymorphous*. Calcium carbonate ($CaCO_3$) is certainly dimorphous, and probably polymorphous. As *calcite* it crystallizes in the trigonal system, scalenohedral class; as *aragonite* it belongs to the orthorhombic system, bipyramidal class; and in *barytocalcite* it forms a mixed crystal with barium carbonate—$CaBa(CO_3)_2$—in the monoclinic system, prismatic class.

Silica (SiO_2) is certainly dimorphous and possibly polymorphous. It commonly crystallizes as quartz in the trigonal system, trapezohedral class; frequently as *tridymite* in the hexagonal system; and has been described as occurring in other forms whose characters are somewhat doubtful.

Titanium oxide (TiO_2) is polymorphous; as *rutile* it is tetragonal with $c = 0.6442$; as *anatase* it is also tetragonal, but with $c = 1.778$; as *brookite* it is orthorhombic.

Isodimorphism.—When chemically analogous compounds form two series of isomorphous salts they are said to be *isodimorphous*. An example of isodimorphism is furnished by the pyrite and marcasite groups.

	Isometric, diploid class.	*Orthorhombic, bipyramidal class.*
FeS_2	pyrite	marcasite
$CoAs_2$	smaltite	saffrolite
$NiAs_2$	chloanthite	rammelsbergite
$(Co,Fe)(S,As)_2$	cobaltite	glaucodote
$NiS_2.Ni(As,Sb)$	corynite	wolfachite

Formulæ of Isomorphous Mixed Salts.—In expressing the composition of mixed salts in which several elements are present in different amounts it is customary to represent the fact of isomorphism by placing the symbols of the elements of like valence within parentheses and separating their symbols by commas. This indicates that these elements may replace one another in any proportion, and is a general formula, not an empirical one. In calculating it from the chemical analysis of a mineral the molecular proportions of the elements having like valence are taken together and compared with the elements of other valences in the mineral. The method is illustrated by the following case of a garnet:

SiO_2..... 41.32 ÷ 60 = .689			
TiO_2..... 0.16 ÷ 80 = .002	.691	3.02	RO_2
Al_2O_3..... 21.21 ÷ 102 = .208			
Cr_2O_3..... 0.91 ÷ 152 = .006	.240	1.04	R_2O_3
Fe_2O_3..... 4.21 ÷ 160 = .026			
FeO..... 7.93 ÷ 72 = .110			
MnO..... 0.34 ÷ 71 = .004+	.685+	3	RO
MgO..... 19.32 ÷ 40 = .483			
CaO..... 4.94 ÷ 56 = .088+			
100.34			

This becomes $3(Mg,Fe,Ca,Mn)O.(Al,Fe,Cr)_2O_3.3(Si,Ti)O_2$. Owing to the very small amounts of Mn, Cr, and Ti present these elements might be omitted from the formula of the mineral, which would become $3(Mg,Fe,Ca)O.(Al,Fe)_2O_3.3SiO_2$, or $(Mg,Fe,Ca)_3(Al,Fe)_2(SiO_4)_3$.

Chemical Analyses express the proportions of the constituents in the material analyzed, and may or may not represent the exact composition of a particular mineral. For it frequently happens that the material submitted for chemical analysis is not purely one mineral, but a mixture of several different substances.

In preparing material for analysis and in interpreting the results of analysis it is of the first importance to consider the purity of the material, which should be investigated optically and its character determined as carefully as possible. Many sources of impurity may be recognized optically. There may be inclusions of other substances, chiefly other minerals. These may be removed by decomposition or solution when they differ markedly in their chemical behavior from the mineral containing them, or they may be separated from it by a magnet or by other mechanical methods to be described later on.

When they cannot be removed the analysis clearly is of the mix-

ture and should be so considered. If the inclosed mineral has a definite, known composition, and the percentage of any one of its constituents is determined by the analysis, its quantity may be calculated and deducted from the whole analysis.

In some cases the inclosed mineral is optically so nearly like the inclosing mineral and is in such microscopically minute particles that it may be overlooked or may not be recognizable under a microscope. Its presence, however, is to be inferred from the chemical analysis, if this differs from an analysis of pure material of a given mineral. For example, the composition of pure hypersthene is undoubtedly expressed by the formula $(Mg,Fe)SiO_3$. It is common for hypersthene to be intergrown in thin microscopic laminæ with augite, which resembles it closely. Such a mixture should contain calcium and aluminium and possibly ferric iron. The presence of these elements in a supposedly pure hypersthene should be considered as chemical evidence of the presence of some other mineral than hypersthene, probably augite. Similarly the presence of calcium in the analysis of a biotite is fair presumptive evidence of the presence of inclusions of apatite, titanite, or some other calcium-bearing mineral frequently found inclosed in biotite.

Besides inclusions of unrelated minerals there may be inclusions of alteration products; that is, the mineral may be more or less altered or decomposed. This may be recognized optically in nearly all cases, as well as chemically by the deviation of the analysis from that of known fresh material.

Another cause of impurity is the adhesion of particles of other substances to crystals of the mineral under investigation, due to imperfect separation of the several minerals by mechanical processes. This can be guarded against by careful inspection of the material before analysis.

The greatest care should be observed in selecting mineral material for chemical analysis, and a statement should be made of the unavoidable impurities known to be present, in order that the results of the analysis may be correctly interpreted.

Minerals entirely free from inclusions of other substances may or may not be chemically homogeneous. Those with a simple or fixed molecule must be chemically homogeneous, as quartz, SiO_2; titanite, $CaTiSiO_5$. But minerals that belong to an isomorphous series, as the lime-soda-feldspars, may or may not have the same chemical composition in all parts of a crystal. They may be chemically homogeneous, or may consist of layers or shells of different compositions.

It is necessary in such cases to study the material optically to determine the actual structure of the crystals when this is recognizable optically, which is the usual case.

Purpose of Chemical Analysis.—For the petrographer a chemical analysis of a mineral is needed for the purpose of determining the exact composition of a mineral which is a mixed salt or one of an isomorphous series, or for identification in doubtful cases. It is evidently unnecessary to analyze quartz or titanite or zircon, for the composition of these minerals is simple and invariable, and they are easily identified optically. The lime-soda-feldspars are so definitely characterized optically that their chemical composition is in most cases as accurately determinable by optical as by chemical methods. In fact optical investigations will give definite information regarding the heterogeneous chemical structure of such minerals that cannot be obtained by chemical analysis of small crystals. The possible presence of potassium-feldspar molecules in crystals of the albite-anorthite series cannot be determined optically as yet and must be discovered by chemical analysis.

The proportions of iron and magnesium in an olivine must be determined chemically; so must the precise composition of such minerals as the pyroxenes, amphiboles, micas, etc. Exact knowledge of the chemical composition of these minerals, together with that of the rocks in which they occur, is becoming of more and more importance to the petrographer. It can only be obtained by rigid quantitative chemical analysis by a skilled analyst, who may also be a petrographer.

The method of procedure must be learned from works on chemistry and lies outside the scope of this book. The special treatment of rock-making minerals may be found in the writings of W. F. Hillebrand,[1] H. S. Washington,[2] and others.

In the identification of the rock-making minerals cases arise in which optical methods alone are insufficient to distinguish between several optically similar minerals when studied in thin section in the absence of other distinctive features, such as possible differences in crystal form. This is the case with the carbonates, calcite, dolomite, magnesite, siderite, which are indistinguishable from one another in thin section when fresh and unaltered.

In such cases use may be made of qualitative methods of chem-

[1] Hillebrand, W. F. Some Principles and Methods of Rock Analysis. Bulletin of the United States Geological Survey, No. 176. Washington, 1900.

[2] Washington, H. S. Manual of the Chemical Analysis of Rocks. New York and London, 1904.

ical analysis to determine the presence or absence of elements that are characteristic of particular minerals. Or reactions may be employed that are characteristic, such as the solubility of the mineral in acid, or the reverse; the formation of gelatinous silica; the evolution of a gas, etc. With the constant improvement of optical methods of research in thin sections and the accumulation of optical and chemical data relating to the rock minerals, the need of qualitative chemical tests is constantly decreasing.

Moreover, the mode of occurrence of a mineral may be a means of discriminating between two that resemble one another closely but have quite different modes of occurrence. Some of the reactions that are useful in the identification of rock minerals are given in what follows, after a description of the methods of preparing the material for chemical investigation.

Preparation of Material for Chemical Analysis.—The amount of material required for complete quantitative analysis depends upon the chemical character of the mineral and the number of different components to be determined. While a satisfactory analysis may be made from as little as 1 gram of material, it is generally desirable to have from 5 to 10 grams to work with. The preparator should always bear in mind that purity of material is more important than the quantity, provided the minimum amount required is obtained.

When minerals occur in crystals several millimeters in diameter it is sufficient to break the rock into small fragments and pick out enough pieces of a mineral for analysis. But in this simple process care must be taken to select pieces free from inclusions, decomposition products, or adhering rock material. In perfectly transparent material this may generally be accomplished by examination under a microscope, unless there are present two or more colorless minerals with similar optical behavior in like-sized fragments. When minerals are more or less opaque in thick fragments their purity may be tested by crushing to thinner pieces, or by means of specific-gravity determinations to detect inequalities in their density.

In all cases careful study should be made of the minerals in thin sections of the rock before separation is attempted in order to know what impurities may be present and to what extent and by what methods they may be eliminated, if possible.

When the mineral crystals are small, or the fragments free from impurities are too small to warrant their separation by hand, they may be isolated by the following methods:

The rock is crushed in an iron mortar by blows of the pestle, with as little grinding as possible in order to avoid powdering the material too fine. For in the process of separation in heavy solutions dust-like powder interferes with the operation by remaining in suspension indefinitely. It must be first removed by washing the rock fragments with water. The larger the mineral fragments the more rapid the separation, since they present less surface in proportion to their mass. But it is necessary for them to be so small that they may each consist of a single kind of mineral. The requisite size of fragment is to be determined by the size of the crystals to be investigated and also by the amount and distribution of inclusions of other minerals when present. For these reasons the crushed rock should be sifted through a series of graded sieves in order to assort the fragments into lots of several sizes which may be examined to determine which fulfills the requirements just named. When more than one kind of mineral is to be separated from a rock each is to be considered in the selection of fragments of proper size.

Owing to the loss of the material in fine powder, which may consist of the more fragile minerals in a rock and may not represent the average composition of the rock, and on account of the material made up of fragments of adhering minerals which must possess specific gravities between those of the separate minerals, it is not possible to use methods of mechanical separation as means of determining accurately the relative quantities of the minerals in a rock. This can be determined with greater accuracy and with less effort by optical measurement in thin sections of most kinds of rocks. Only in the case of very coarse-grained rocks could the method of mechanical separation give more reliable results. It may be used with reasonable accuracy in determining quantitatively the mineral composition of coarse pegmatites.

In general it is only necessary to proceed far enough with the operation to supply the requisite amount of material for chemical analysis or for other purposes. When the sifted fragments have been washed free from dust they may be separated into different minerals by means of specific-gravity solutions, by an electromagnet, or by chemical means.

Micaceous minerals may be separated more or less completely, or concentrated, by allowing the fragments containing them to roll over a smooth surface, as over a sheet of paper or glass. The flat scales adhere or lodge on the smooth surface, while the other fragments roll off. It is sometimes advisable to separate the mica

in this manner before introducing the fragments into a heavy solution in which the mica may remain in suspension for a long time, interfering with the separation of other minerals.

Specific-gravity Separation. — Minerals that differ from one another appreciably in density may be separated by assorting them in a current of water or by letting them settle or float in a liquid of nearly their own density.

In Water.—Separation in a current of water is the process familiarly known as washing, as gold is washed from other materials. It is applicable to cases where there is a marked difference in the density of the minerals, as the separation of cassiterite, magnetite, pyrite, chromite, zircon, rutile, corundum, and other minerals of like density from quartz, feldspar, and the lighter minerals. The process is simple and needs no description; by repeating it the separation becomes more perfect. It may be accomplished by various devices according to the convenience or ingenuity of the operator. By controlling the force of the current in an upright tube it is possible to separate minerals differing but little in density, but the shape and size of the fragments become relatively greater factors in such cases. The extreme instance is that of mica, or a micaceous mineral, which in thin flakes offers a great surface as compared with the mass and is readily floated off in a current.

In Heavy Solutions.—By placing mineral fragments in a solution whose density is greater than that of one mineral and less than that of another they may be separated by the floating of the lighter and the sinking of the heavier mineral. A number of heavy solutions have been employed for this purpose. They are described in the section on relative density.

Having previously studied the rock or the mixture of minerals to be separated, the specific gravity of the solution to be used is known approximately. The concentrated heavy solution with maximum density is diluted to the required density, which is tested most conveniently by means of crystals whose specific gravity is known; one nearest and higher than the required density being floated in the solution, which is diluted slowly until the crystal remains in any part of it without rising or sinking.

Mineral indicators may be prepared by carefully determining the specific gravity of selected crystals, and keeping them for the use just mentioned. Since the specific gravity of any crystal is affected by inclusions of other substances, it is necessary to determine the density of each particular crystal to be used as an indicator, and

not assume it to be the same as that of another crystal of the same mineral from the same locality. The accompanying list of minerals is given to guide one in selecting material for indicators:

Sulphur	2.05 –2.09	Tourmaline	2.98 –3.20
Chabazite	2.08 –2.16	Fluorite	3.180–3.189
Opal	2.1 –2.2	Apatite	3.17 –3.23
Heulandite	2.18 –2.22	Diopside	3.19 –3.28
Analcite	2.22 –2.29	Epidote	3.25 –3.5
Apophyllite	2.3 –2.4	Axinite	3.27 –3.29
Gypsum	2.314–2.328	Vesuvianite	3.3 –3.44
Obsidian (rhyolitic)	2.344–2.36	Titanite	3.4 –3.56
Leucite	2.45 –2.50	Topaz	3.4 –3.65
Adularia	2.56 –2.57	Acmite	3.50 –3.55
Nephelite	2.55 –2.65	Grossularite (Wakefield)	3.525
Albite	2.62 –2.65	Spinel	3.52 –3.58
Quartz (Herkimer)	2.660	Staurolite	3.65 –3.75
Labradorite	2.69 –2.70	Andradite	3.73 –3.85
Beryl	2.69 –2.70	Siderite	3.83 –3.88
Calcite	2.713–2.723	Corundum	3.95 –4.10
Wollastonite	2.8 –2.9	Almandite (Ft. Wrangel)	4.093
Prehnite	2.8 –3.0	Willemite (New Jersey)	4.11 –4.19
Aragonite	2.93 –2.95	Zircon	4.2 –4.86
Tremolite	2.93 –3.03		

In any case the actual density of the heavy solution may be determined by the Westphal balance (p. 95) upon removing a small portion of the solution to another vessel.

The minerals heavier than the solution settle to the bottom and may be removed, those that float may be separated by still further diluting the solution until another mineral settles, and so on.

The separation is conveniently accomplished by means of specially constructed apparatus, but may be performed in a simple vessel with more or less inconvenience caused in removing the floating material which commonly adheres to the sides of the vessel containing the heavy solution.

The most convenient apparatus for general use with solutions at ordinary temperatures is one devised by Harada [1] and modified by Brögger [2] (Fig. 1). It consists of a glass vessel closed at the top by a ground-glass stopper, and having two glass cocks, one near the middle and the other near the lower end. When the lower one of these is shut a heavy solution of nearly the required density is placed in the vessel, and the mineral fragments are introduced into it. When

[1] Neues Jahrb., BB. I., 1881, p. 457.

[2] Geol. Fören. in Stockholm Förhdl., 7, 1884, p. 417.

the stopper is in place the whole is thoroughly shaken and allowed to stand until the heavier material has settled and there is a space of clear liquid between it and the floating material (Fig. 1*a*). The middle cock is then closed, and the apparatus shaken thoroughly in order to further the separation of the previously separated portions in the two parts of the solution, because in most cases neither is entirely free from other material, a small amount of the lighter being carried down by the heavier, and some of the heavier being kept up by the lighter. After the second shaking the vessel is placed upside down, as in Fig. 1*b*. When the separation has taken place in the two parts of the heavy solution the vessel is slowly tilted so that the heavy and light minerals change places (Fig. 1*c*). When

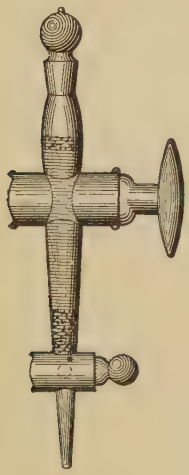


FIG. 1*a*.

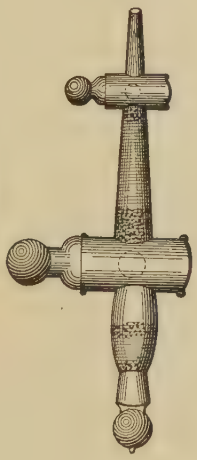


FIG. 1*b*.

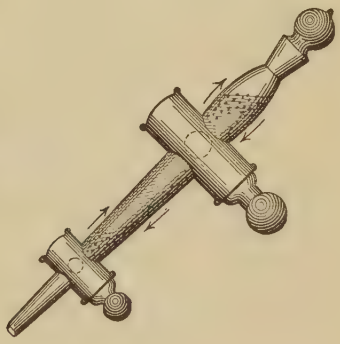


FIG. 1*c*.

the light material in the lower portion and the heavy material in the upper have just reached the middle cock it is turned slowly, letting the heavy and light materials pass one another without mingling. When they have passed into the lower and upper portions of the vessel the middle cock is closed and the operation repeated if it is thought the separation is not complete. Afterwards the heavy material is drawn from the lower portion through the bottom cock.

The mineral so separated is removed from the heavy solution, which is filtered and concentrated for future use. The mineral fragments are washed and after drying are examined to see whether they contain fragments of other minerals, which are not infrequently found adhering to the principal mineral. If these are few in num-

ber they may be removed by hand. Otherwise the fragments should be reduced in size and the whole process repeated.

When solutions are used that require heating to produce liquidity a form of apparatus devised by Coutollence and modified by Penfield is found convenient.[1] It is shown in section about one third natural size in Fig. 2. The best solution to use is thallium-mercuro-nitrate, which attains a maximum density of 5.3 at 76° C. This solution is quite fluid when concentrated and may be diluted to any extent with water.

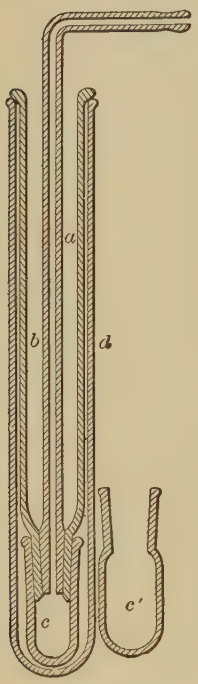


FIG. 2.

As described by Penfield, the glass tube *b*, about 20 cm. long by 2.2 cm. internal diameter, is narrowed below and fitted with well-ground joints to the cap *c* and the hollow stopper *a*. These parts fit loosely in a large test-tube *d*. For holding and heating the apparatus it may be placed in a metal test-tube holder and set in a tall beaker filled with hot water.

In order to make a separation the heavy solution is first melted in a dish on a water-bath and diluted until it has approximately the specific gravity of the minerals to be separated, but a little higher. The stopper *a* is removed, the apparatus warmed and about half filled with the solution. The mineral fragments are added and thoroughly mixed, which may be accomplished by blowing air through a small glass tube. Water is then added little by little until the desired density is obtained and a certain mineral sinks to the bottom. In order to remove this the stopper *a* is warmed and inserted, when the cap *c* is withdrawn and the contents washed out with warm water. Upon replacing the cap and diluting the solution further other minerals may be separated. When larger amounts are to be separated a large cap *c'* may be used.

The advantage of this solution over the Sonstadt-Thoulet solution is its higher specific gravity, which is as high as that of hematite. But it has the disadvantage that its specific gravity cannot be easily determined by means of the Westphal balance. Since its density changes with its temperature, the determination should be made

[1] Am. Jour. Sci., 50, 1895, p. 446.

within the tube *b* of the separating apparatus at the time of the separation. Other forms of apparatus are described by Rosenbusch and Wülfing in their work on the rock-making minerals.[1]

W. J. Sollas [2] employs a graduated tube in which layers of methylene-iodide, having successively lower specific gravities, are superimposed. Rock fragments prepared as already described are introduced and allowed to settle to their respective places in the column. From the distribution and amount of the fragments in various layers an estimate of the relative proportions of the different minerals is obtained. The method, however, is subject to considerable error and is less accurate than optical methods of measurement of the relative quantities of the constituents of a rock.

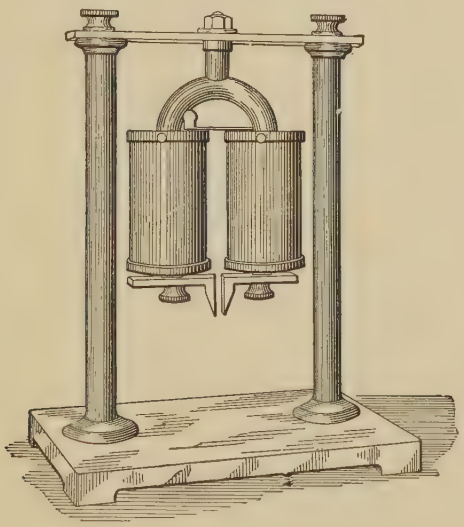


FIG. 3.

Separation by Electromagnet.—Metallic minerals that are magnetic and minerals inclosing magnetic minerals may be separated from non-magnetic minerals by means of an ordinary magnet passed over fragments spread upon paper. But other iron-bearing minerals which do not ordinarily exhibit magnetism may be attracted to a strong electromagnet. Their power of attraction is not directly

[1] Mikroskopische Physiographie der Mineralien und Gesteine, 4th ed., Vol. I, Part I, p. 422. Stuttgart, 1904.

[2] Quart. Jour. Geol. Soc., 58, 1902 p. 163.

proportional to the percentage of iron present. It varies with different iron-bearing minerals, which may be separated from one another by varying the strength of the electromagnet, or more conveniently by changing the distance between the poles of the magnet. For this purpose they may be provided with movable bars, one end of each having a point projecting at right angles, as shown in Fig. 3 (after Rosenbusch and Wülfing). The bars are fastened by screws to the poles of the magnet. Mineral fragments are brought in contact with these points, to which the more magnetic adhere. When the others are withdrawn those adhering may be dropped into a receptacle by breaking the current. By repeating this operation a number of times the separation becomes more perfect.

Separation by Chemical Means.—When minerals that occur together in a rock are differently acted on by any acid it is often possible to dissolve or decompose one without affecting the other. It is only necessary to consider the behavior of the minerals with respect to different reagents and conduct the operation accordingly.

Most silicates may be separated from carbonates by dissolving the latter in weak acids. The silicates not easily attacked by hydrochloric acid may be separated from those that are easily attacked.

Hydrofluoric acid acts upon the silicates and quartz with sufficient difference to permit of the separation of the less readily attacked mineral. When to the concentrated acid mineral fragments are added rapidly enough to produce a considerable rise of temperature, but not so as to produce ebullition, they will be attacked in a definite order; so that by interrupting the operation by adding water in sufficient amount one constituent or more may be removed, leaving the others unattacked. The fragments should be constantly stirred during the operation. The first to be decomposed is rock glass, when present. So that by properly timing the process the crystals in a glassy rock may be separated from the glass base. They will at first be coated or accompanied by a jelly, which may be removed by washing and rubbing with the fingers, while the jelly is wet, or after it has been dried to a powder. The minerals are attacked in the following order: feldspars and feldspathic minerals, leucite, nephelite, sodalites, quartz, and lastly the ferromagnesian minerals, pyroxenes, amphiboles, olivines, etc. Hydrofluoric acid may also be used with hydrochloric or sulphuric acids for the more rapid isolation of the least soluble minerals, such as zircon, rutile, spinel, tourmaline, etc.

In all cases the material separated for chemical analysis should be thoroughly washed and freed from adhering matter before being submitted to analysis.

Chemical Investigation of Rock Sections.—There are some cases in which it is desirable or necessary to make a chemical test directly on the rock section, when optical tests are indecisive. But with constant improvements in optical methods such cases are becoming fewer, as already remarked.

Tests may be made to determine the solubility of a mineral in section; its mode of decomposition in acid, as the formation of gelatinous silica; the presence of one or more chemical constituents that may be characteristic, as by the liberation of carbon dioxide, or the precipitation of a compound of iron, chlorine, etc. Changes which take place upon ignition may be characteristic, indicating the presence of water of crystallization, or of ferrous iron, etc.

In certain cases it may be advisable to remove soluble constituents that cloud the other minerals and interfere with their optical study, as when a rock is clouded with minute particles of iron oxide, carbonaceous matter, or carbonates.

Preparation of Sections for Investigation.—If a section is to be examined chemically, it is necessary to expose a surface of mineral free from Canada balsam, either by removing balsam already present, or by not covering the rock section in the first instance.

If the rock section is prepared especially for chemical study, the upper surface after final grinding is left free and is washed clean. It is not necessary to polish the surface, unless for optical purposes, for the rougher surface exposes a greater area to the chemical reagent than an even surface. In case a limited portion of the rock section is to be exposed to chemical action the remainder must be covered with balsam. This may be done by applying the balsam carefully to the parts to be covered up and leaving the rest free from it; or the whole surface may be covered with balsam, and the part to be attacked chemically may be exposed by removing the balsam from it with alcohol or ether applied with a properly sized brush or a pointed stick. Afterwards the surface is washed with water until the mineral is clean. This operation may be more definitely and readily localized by covering the whole section with a cover glass in which a hole has been made of the proper size, which is placed directly over the crystal to be tested. The balsam is then removed as just described. Cover glasses may be prepared for this purpose by coating them with wax and uncovering so much as is needed for an open-

ing, which is made by dissolving the glass with hydrofluoric acid; afterwards the wax is removed.

In case the rock section is to be heated to redness it is removed from the glass on which it was mounted for grinding, freed from balsam on both sides by alcohol or ether, and washed.

Chemical Tests.—The determination of the relative solubility of minerals may be made by applying a drop of reagent of the required strength and permitting it to act for any given length of time and at low temperature, or at higher temperature, below the melting-point of balsam. The changes that may take place in the optical behavior of the mineral may be noted with a microscope. If there is danger of the acid affecting the lens, the acid may be removed before optical examination or a longer-focussed lens employed.

When solution takes place with evolution of gas the action may be watched and its locality noted by covering the exposed surface with a film of water and a glass cover, and applying weak acid at the edge of the cover glass and allowing it to diffuse slowly over the mineral or rock surface. When decomposition takes place with the separation or precipitation of a compound it is desirable to limit this deposit to the surface of the mineral from which it originates. This is accomplished by causing the reaction to take place with as little diffusion as possible, since this tends to spread the precipitate over the surface of other minerals. For this reason as thin a film of the reagent as possible is employed, and the strength should be such as to produce the most rapid rate of decomposition. It is also advantageous to add the reagent a little at a time.

When the separated compound is not readily noticeable optically, on account of being colorless and isotropic, as is the case with gelatinous silica, or when its presence does not affect appreciably the optical behavior of the mineral beneath it, it may be rendered more noticeable by staining. This may be done by carefully washing the surface of the section with running water to remove the chemical reagent without disturbing the deposit of silica or other compound, and applying a staining liquid, as an aniline color, which is allowed to penetrate the finely divided material of the precipitate, which remains colored after the excess of staining liquid is rapidly washed away.

When a chemical reaction in the precipitate may be brought about that will produce a characteristic coloring, this may be used not only to show the presence of the precipitate, but to determine

its character, as when a colorless iron-bearing compound is changed into a characteristically colored one.

When it is desired to determine the presence of one or more characteristic elements or compounds in a mineral in a rock section, the mineral is exposed to the action of the proper reagent and the test made in the solution or the precipitate when present, as the case may be. The solution may be tested directly as it is obtained on the rock section, or it may be removed by means of a fine capillary tube easily prepared by drawing thin a glass tube. It may be transferred to a watch glass and tested. Some of the reactions that may be employed are described below.

As already said, there are few instances in which an appeal to chemical tests in the determination of the minerals in rock sections is needed, for in most cases the optical properties, or these in connection with the mode of occurrence, of a mineral are sufficient to place its identification beyond reasonable doubt. In certain cases in which a chemical test is desirable and the crystals are insoluble in ordinary acids in thin sections, they must be separated and tested by the usual methods of qualitative analysis, including blowpipe tests. For such cases the student is referred to text-books on determinative mineralogy, especially to the works of S. L. Penfield.[1]

Special Reactions.—The special microchemical methods devised for testing minute quantities of minerals are valuable in exceptional cases, and in the hands of a chemist may be found advantageous in the determination of minerals whose optical characters are unknown. They are so seldom needed in the study of rocks that they are not described in this book, but may be found in the works of Behrens, Boŕicky, Streng, Bourgeois, and others. A complete bibliography of the subject may be found in Rosenbusch-Wülfing's work already cited.[2] The more recent and comprehensive treatises are the following:

Mikrochemische Technik. H. Behrens. Hamburg-Leipzig, 1900. pp. 68.

Kurze Anleitung zur mikroskopischen Krystallbestimmung. J. L. C. Schroeder van de Kolk. Wiesbaden, 1898. pp. 58.

Analyse microchimique. L. Bourgeois. Paris, 1892. pp. 14.

[1] Brush-Penfield. Determinative Mineralogy and Blowpipe Analysis, 15th ed. New York. Endlich, F. M. Manual of Qualitative Blowpipe Analysis and Determinative Mineralogy. New York, 1892. Dana, E. S. Text-book of Mineralogy. New York, 1902.

[2] Loc. cit., Part I, p. 435.

There are, however, certain reactions which are necessary and may be applied to the examination of rock sections. They are those by which the carbonates, calcite, dolomite, magnesite, and siderite, and the silicates, sodalite, haüynite, and noselite, may be distinguished from one another.

The *carbonates*, *calcite*, *dolomite*, *magnesite*, and *siderite*, may be distinguished, so far as is possible qualitatively, since they grade into one another by isomorphous mixture of calcium, magnesium, and iron carbonates, by noting their different behavior toward acids as well as the relative abundance of their constituent basic metals.

Calcite dissolves in acetic acid with strong evolution of carbon dioxide, while dolomite is attacked but slowly by the cold acid. The difference of behavior may be increased by adding to dilute acetic acid ammonium phosphate, which precipitates magnesium phosphate on the surface of the attacked crystal, thus interfering with the further solution of the crystal. This takes place when there is 10 or 15 per cent. of $MgCO_3$ in calcite.

The rate at which the operation effects the stoppage of the decomposition depends on the strength of the solution and the amount of $MgCO_3$ in the crystal. The proportion of ammonium phosphate to acetic acid to water employed by G. Linck [1] is 2 : 3 : 10.

Another method depends upon the greater precipitation of alumina from a solution of aluminium chloride upon the more rapidly decomposed mineral. By introducing coloring matter into the solution this shows itself in the precipitate after the colored solution has been washed away. Such a solution has been made by J. Lemberg [2] with 4 parts of aluminium chloride (dry), 6 parts of logwood, and 60 parts of water, which is boiled for half an hour, with the addition of the amount of water lost by evaporation. The solution, placed on a section containing calcite and dolomite for five or ten minutes, deposits a violet coating on the calcite but not on the dolomite, the coating on the calcite appearing after the solution has been washed away.

Magnesite is not acted on by cold hydrochloric acid, and the solution in hot acid contains no calcium or but little. The test for calcium may be made by adding to the solution, which has been removed from the rock section to a watch glass, a small amount of

[1] Inaug. Dissert. Strassburg in Els., 1884, 17.

[2] Zeitsch. d. deutsch. geol. Gesell., 40, 1888, p. 357.

dilute sulphuric acid, which precipitates hydrous calcium sulphate in the form of gypsum crystals. If there is but little calcium present, the sulphate may remain in solution until the evaporation of the liquid causes it to crystallize in gypsum crystals with characteristic shapes.

Siderite is acted on slowly by cold acids, but is completely dissolved by hot hydrochloric acid. The presence of iron in the mineral, which is in the ferrous state, may be determined by adding to the solution potassium ferricyanide, resulting in the precipitation of ferrous ferricyanide having a deep-blue color. If to the solution containing iron chloride is added ammonium sulphide, there is precipitated iron sulphide which is black. The precipitate may be deposited by covering the rock section with a thin film of dilute hydrochloric acid to which has been added a little of either of the reagents just named. The carbonates containing iron will be coated with a blue or black precipitate according to the reagent used.

The silicates *sodalite*, *haüynite*, *noselite*, and *analcite* are decomposable in acetic or nitric acids with the separation of gelatinous silica. The chemical distinctions rest on the presence of chlorine in sodalite, and its absence from the other minerals; also on the presence of sulphur in haüynite and noselite, and the presence of calcium in haüynite and its absence from noselite or its presence in extremely small amounts.

The presence or absence of chlorine may be determined by exposing the surface of the minerals to be tested to very dilute nitric acid containing a very little silver nitrate. The mineral containing chlorine will be coated with gelatinous silica clouded with silver chloride. A similar test may be made with other reagents. The presence of sulphur and calcium may be determined by allowing the gelatinous silica obtained by the decomposition of the mineral in hydrochloric acid to dry, when crystals of gypsum will form according to the amount of calcium present.

The presence of sulphur in the absence of calcium may be determined by subjecting the crystal surface to the action of dilute acetic or hydrochloric acid containing a little barium chloride. When sulphur is present barium sulphate will be precipitated in crystals with orthorhombic symmetry.

The test for *magnesium* by ignition with a solution of cobalt nitrate may be used to identify talc when indistinguishable from muscovite. Upon being heated to redness with cobalt nitrate, talc assumes a light pink or flesh color.

Some aluminium minerals may be tested similarly for aluminium, becoming blue. But the reaction is only applicable to minerals that are not fused at this temperature, for glasses generally assume a blue color when fused with cobalt nitrate

Carbonaceous matter and *graphite* may be detected and also removed from a rock section by heating it to redness. When they are mingled with iron oxide it is necessary to treat the section with acid to dissolve the iron oxide, the two processes being repeated several times if it is desired to remove them completely.

CHAPTER II.

PHYSICAL PRINCIPLES AND CHARACTERS IN PART.

THE physical properties of a crystal must be dependent in the first instance on the chemical composition of the crystal, more specifically on the chemical constitution, or atomic structure, of the physical molecule of the crystal, and to a larger extent on the arrangement of these molecules in the crystal, that is, on the molecular structure.

If the atoms of the component elements be supposed to have a definite arrangement in a molecule, and the molecules have a definite arrangement in a crystal, then the atoms of the elements in a crystal must have a definite arrangement, so that the conception of a molecular structure in a crystal involves that of an atomic structure, to either of which may be referred the characteristics of the physical properties.

The extent to which this relationship is demonstrable differs with the kind of physical property; and with some the dependence is more clearly on the chemical composition, with others more evidently on the molecular structure. An example of the first group is the *density*, which is closely related to the chemical composition, but not rigidly, since the same substance or compound in different modes of crystallization has different densities. An example of the second group is the *hardness*, for, while appearing to depend to a great extent on the composition, it differs in some instances most remarkably in different kinds of crystals of one substance, as in diamond and graphite; in other instances in different planes in one and the same homogeneous crystal; and even in opposite directions in the same plane of one crystal, as in the basal plane in calcite.

Some physical properties may be said to depend directly on the physical molecules of a crystal and on their arrangement, as must be the case with the density, hardness, elasticity, cohesion, crystal form, and mode of solution. Of these, some are more closely related to the character of the individual molecule, as the density; others

more particularly to the molecular arrangement, as the crystal form, more properly the crystal symmetry; whereas the crystal habit probably bears a strong relationship to the individual molecule.

Other physical properties are less directly connected with the physical molecules of a crystal and with their arrangement. This must be the case with the optical properties and those of thermal radiation and conduction, which exhibit higher symmetry than exists in the arrangement of the molecules of a crystal. Magnetic and electrical properties are closely related to the optical and thermal, but the electrical are more closely connected with molecular arrangement, as shown by pyroelectrical phenomena.

While all of these characters and relationships are essential to a comprehensive understanding of the nature of minerals and should be known to the petrographer, they are not all equally applicable to the study of rocks and for this reason will not all be reviewed in this book. Moreover, one of them, crystal form, is so important and extensive a subject by itself that it is assumed that the student has acquired familiarity with it in works on crystallography, or more general works on mineralogy. Only so much of these groups of physical characters will be discussed in this connection as seems necessary to the work of the petrographer, as such, or to a clear understanding of the methods of description followed in this book.

It seems advisable to begin with a brief statement of the theory of the molecular structure of crystals, and of some fundamental concepts of symmetry and of crystal form connected with it.

Molecular Structure of Crystals.—A consideration of those physical properties dependent on direction in crystals leads to the conclusion that any point within a crystal is physically like every other point within it; and since in all parallel lines the physical properties are alike, and these depend on molecular forces along such lines, it follows that the molecules of a crystal must be similarly spaced and oriented along all parallel lines; and, further, parallel planes in a crystal must pass through similarly arranged molecules since parallel planes contain parallel lines. Consequently a crystal must be built up of molecules so arranged as to present a regular network of molecules, or of similar clusters of molecules, such

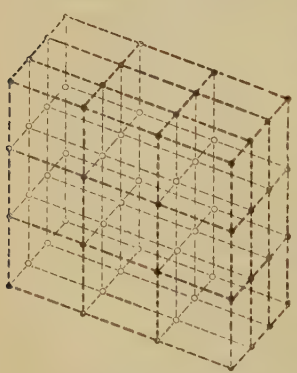


FIG. 1.

that parallel lines from each molecule intersect other molecules at like distances. A simple network is illustrated in Fig. 1.

The geometrical possibilities of such networks have been discussed with reference simply to the location of the molecules, as points in a system, without regard to the possible shape or polarity of the molecules, and by successive elaborations of the systems of points it has become possible to account for all of the physical variations observed in crystals without taking into account the possible form of the molecule. This conception has been formulated gradually by Frankenheim, Bravais, Sohncke, Schönflies, Federow, and others.[1] The most general statement framed by Sohncke[2] is that:

A crystal consists of a finite number of interpenetrating regular point systems, which all possess like and like-directed coincidence movements. Each separate point system is occupied by similar material particles, but these may be different for the different interpenetrating partial systems which form the complex system.

If we assume that each separate point system is made up of the atoms of one element, then the structure may be termed an atomic structure, and a molecule of a crystal or chemical compound may be assumed to be such a cluster of the different atoms as represents their arrangement with respect to one another.

In the most complex expression of the theory there are 230 kinds of point systems which satisfy the conditions imposed upon the problem by the physical phenomena observed in crystals. These 230 may be grouped in 32 classes according to the degree of symmetry involved in each point system, and these 32 classes may be referred to 7 axial systems, that correspond to the 7 crystallographic systems to which it is customary to refer all crystals.

Crystal Planes and Edges.—Physically homogeneous crystals are commonly bounded by flat planes and straight edges. The crystal plane corresponds to a plane of molecules in a point system, and the edge where two faces meet represents a line of molecules in the point system which is common to two planes in the system. Crystal faces or planes representing like arrangements of molecules should be physically alike. The angles between intersecting planes depend

[1] See the statement of the theory in Groth's Physikalische Krystallographie, etc., also the bibliography of the subject in Dana's Text-book of Mineralogy, 1902, p. 22.

[2] Zeits. f. Kryst., 14, 431 et seq. See also Chemical Crystallography, by P. Groth; translated by Hugh Marshall, p. 12. New York, 1906.

upon the character of the molecular arrangement and the position of the planes in it; they should therefore be definite and constant between planes similarly situated in all crystals of a given compound having like molecular arrangement. This is the law of the constancy of interfacial angles between homologous planes of all crystals of a given kind, and of a given compound.

This relation is illustrated in Fig. 2, representing one plane of molecules in a simple network. The intersecting lines represent

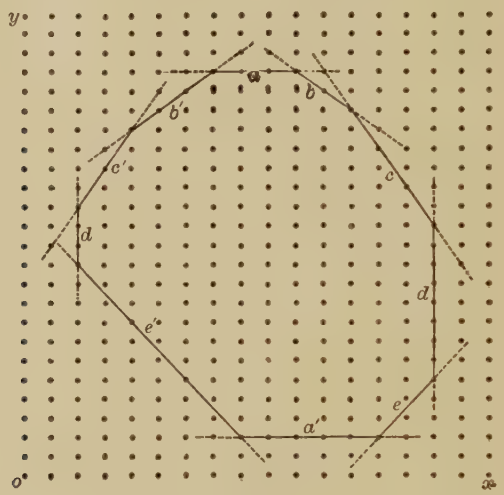


Fig. 2.

traces of planes differently situated in the network, all of which are normal to the plane $ox \cdot oy$, the lines of molecules along ox and oy being at right angles to one another. The planes b and b' are equally inclined to a and a'. They are each equally inclined to one plane of each of the other pairs of planes that have like molecular positions, as c, c'; d, d'; e, e'.

Since molecules in parallel lines are uniformly spaced with respect to one another, it follows that the angular positions of two or more intersecting planes bear regular relations to one another, which relations when expressed in terms of the intersection of such planes along lines of molecules taken as axes of reference, coördinate axes, ox, oy, are found to be rational ratios. The commonest ratios observed on crystals are between simple small numbers, as 1 : 2, 1 : 3, 1 : 4, 2 : 3, 3 : 4, etc. This is the fundamental law of the rationality of the

indices, or ratios of the intercepts of the facial planes on coördinate axes.

This relationship is illustrated in Fig. 3, in which the lines *a*, *b*, *c*, *d*, *e*, represent the traces of planes having different molecular positions and intersecting the axis *ox* at the distances 6, 12, 18, 24, 30, and the axis *oy* at 12. The ratios of the intercepts are: $x:y=1:2$ for *a*, 1 : 1 for *b*, 3 : 2 for *c*, 2 : 1 for *d*, 5 : 2 for *e*. It is apparent also from the diagram that those planes with the simplest ratios of the intercepts will be the commonest because in them the molecules are closer together than in planes in other directions.

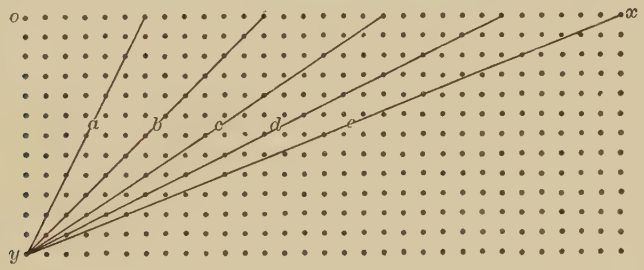


FIG. 3.

Crystallographic Axes.—The coördinate axes to which the planes of a crystal may be referred for geometrical description will yield the simplest expressions for the intercepts, or indices, of the commonest faces of a crystal when the axes coincide with lines of molecules common to these plane faces, that is, when they are parallel to the edges of intersection of the commonest crystal faces. The choice of edges for coördinate axes is further controlled by the symmetry of a crystal, since it is desirable that similar faces or those symmetrically alike should have similar indices, that is, should intersect the crystallographic axes similarly. This has led to the selection of definite directions for the crystal axes in crystals of certain kinds of symmetry.

In five systems of the seven there are three axes of reference, or crystal axes. In the remaining two systems it is customary to employ four axes, though one of these systems could be referred to three axes. And in some methods of treatment the two systems that are referred to four axes, since they are in the same position with respect to one another, are described as one system (the hexagonal), making six systems instead of seven. In this book the seven systems are recognized, on a basis of the symmetry.

In the most general case the three axes are designated by the letters a, b, c, and the angles between each two of them by α, β, γ (Fig. 4), the angle α being between the axes b and c, and so on.

The molecular spacing along the line, or axis, a is not necessarily the same as that along the line b or c. This depends upon the kind of point systems to which a crystal belongs. When the spacings on the three axes are unlike the ratios between the intercepts are not rational numbers. This is indicated by the ratios between the intercepts of a plane intersecting the three axes as in Fig. 5. For, according to the statement already made, the distance of the intersection of the plane with a, b, and c may be considered as occurring at a distance of m molecules on a, n molecules on b, and p molecules on c. And assuming that the distance between successive molecules in each axial line is the unit of linear measurement on each of these

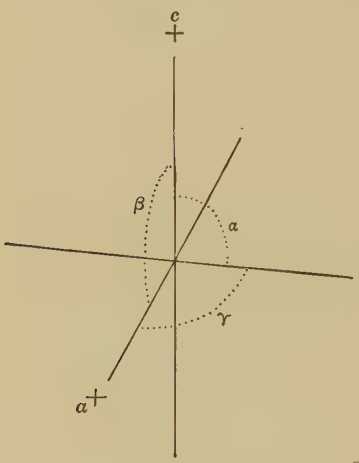


Fig. 4.

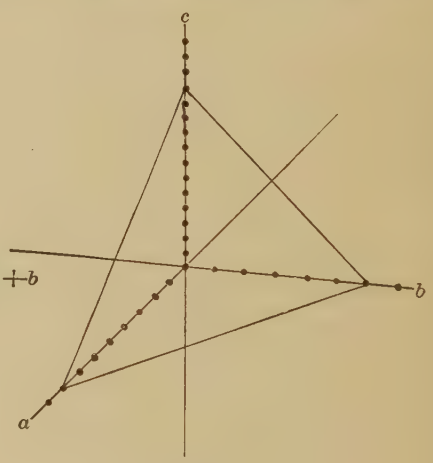


Fig. 5.

axes, and designating these units by a, b, c, then the intercepts of the plane on the three axes are ma, nb, pc. Now it has been found by measurements of the angular position of the faces of a crystal that the ratio $ma : nb : pc$ is not rational unless in the directions of the axes a, b, c, the crystal is physically the same, that is, has like molecular spacing in these directions. But the ratio between the intercepts ma, m_1a, m_2a, of several different planes with one crystal axis is rational. Thus the ratio $ma : m_1a : m_2a$ is rational.

It is customary to select the intercepts of some one plane intersecting three crystal axes as units of length on these axes with which

to compare the intercepts of other planes on the same crystal. Such a plane is called the unit plane, or form, and the ratio between the three intercepts is given as the unit lengths of the three axes a, b, c. Moreover it is customary to reduce this ratio so that one member of it becomes unity. Thus the axial ratio in albite is stated as $a:b:c=0.6335:1:0.5577$. When the ratio between the intercepts on two or three crystal axes is rational, the axes are physically alike, and are designated by the same letter, a. The plane then chosen for the unit of comparison is one cutting similar axes in a like manner, so that the unit lengths on such axes become the same, and are made unity. Thus in zircon the axial ratio is $a:a:c=1:1:0.64037$. This is expressed briefly by $c=0.64037$. When all three axes are physically alike they are all designated by a, and the axial ratio is $a:a:a=1:1:1$, which need not be stated, the name of the system, *isometric*, indicating the ratio between the axes.

Symbols—Indices.—There are several methods in use for expressing the position of a crystal plane with reference to the axes of the crystal. The parameters or intercepts on each axis may be stated as multiples of the units of measurements on each axis as $ma:nb:pc$, in which m, n, and p may be whole numbers or proper fractions. In case any parameter is a fraction, as $2a:\frac{3}{2}b:3c$, the expression may be reduced to whole numbers by clearing of fractions, as $4a:3b:6c$, since this is equivalent to moving the plane parallel to itself, which does not affect its angular or crystallographic position. Similarly any expression of the parameters may be stated in the form of fractions whose numerators are unity, as $\frac{1}{3}a:\frac{1}{4}b:\frac{1}{2}c$. This is equivalent to moving the plane parallel to itself nearer to the center of the crystal axes.

The denominators 3, 4, 2, of the fractions in this last expression are called *indices* of the plane and when written alone 342 are known as the Miller symbol. The first number always refers to a, the second to b, the third to c. They may be obtained by taking the reciprocals of the parameters in the expression $4a:3b:6c$, $\frac{1}{4}$, $\frac{1}{3}$, $\frac{1}{6}$, and clearing of fractions by multiplying by 12. The Miller symbols are those most commonly used, and are employed in this book.

The expression of the parameters in the form $ma:nb:pc$, as $4a:3b:6c$, is known as the Weiss symbol. It has been abbreviated by Naumann by first reducing it to a form in which the parameter on a is unity, as $1a:nb:mc$, and expressing this as mPn; the parameter on the vertical axis being put first, and that on the b axis last. The expression $4a:3b:6c$ would become $\frac{3}{2}P\frac{3}{4}$. In the iso-

metric system P is replaced by O. Naumann symbols are used in many works on petrography, especially in German, but they are generally accompanied by the Miller symbols. Other symbols have been, and are, employed by different mineralogists and may be found described by Goldschmidt.[1] A few examples of symbols in the three systems mentioned will be sufficient to illustrate their relations to one another.

Weiss.	Naumann.	Miller.
$1a : 2b : 3c$	$3P2$	632
$1a : 1b : 2c$	$2P$.	221
$1a : 3b : 1c$	$P3$	313
$1a : \infty b : 2c$	$2P\infty$	201
$1a : 3b : \infty c$	$\infty P3$	310
$1a : \infty b : \infty c$	$\infty P\infty$	100
$1a : 1b : 1c$	P	111

When a plane intersects an axis on the negative side it is indicated in the Miller symbol by placing a negative sign over the proper index, as $\bar{2}21$, $3\bar{1}\bar{2}$, etc.

Symmetry.—The physical properties as well as the geometrical forms of crystals exhibit various degrees of likeness or symmetry in various directions which are characteristic of different minerals. But all the properties of any crystal do not exhibit the same amount of symmetry. There are three kinds of simple symmetry recognized in crystals, besides several kinds of compound symmetry.

(*a*) With respect to a point: a *center of symmetry.*

(*b*) With respect to a line: an *axis of symmetry.*

(*c*) With respect to a plane: a *plane of symmetry.*

A *center of symmetry* is a point through which a line in any direction passes through like points on a geometrical body. Thus the center of a cube is a center of symmetry

An *axis of symmetry* is a line about which two or more planes or physically homologous directions in a crystal are similarly and uniformly disposed, so that by rotating them about the axis of symmetry they may be made to exactly occupy one another's previous positions. The number of times this operation of coincidence may be accomplished in a complete rotation of 360°, when the original position is reached, is limited to four possibilities: (*a*) a twofold rotation of 180°, (*b*) a threefold rotation of 120°, (*c*) a fourfold rotation of 90°, and (*d*) a sixfold rotation of 60°.

A crystal may possess more than one axis of symmetry and more

[1] Index der Krystallformen der Mineralien, 3 vols., 1886–1891.

than one kind of axis of rotation. These must intersect at certain angles, and the number and kinds that may occur together are limited. In a cube the normals to the center of the faces are fourfold axes of rotation, of which there are three (Fig. 6); the diagonals through the center connecting the corners are threefold axes, of which there are four; the diagonals through the center connecting the middle of opposite edges of the cube are twofold axes of rotation, of which there are six.

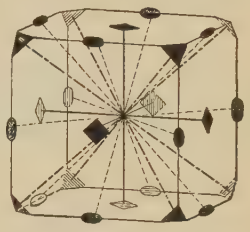


Fig. 6.

A *plane of symmetry* is one that divides the crystal into equal parts so placed that for every point in one part there is a corresponding point on the opposite side of the plane of symmetry along a line *normal* to this plane. In Fig 7 the line *ab* is the projection of a plane of symmetry which is normal to the plane of drawing of the

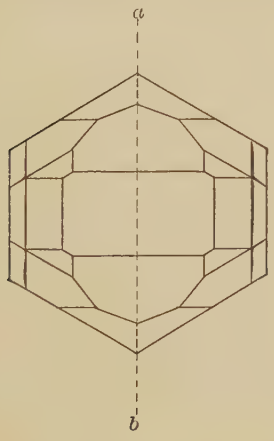


Fig. 7.

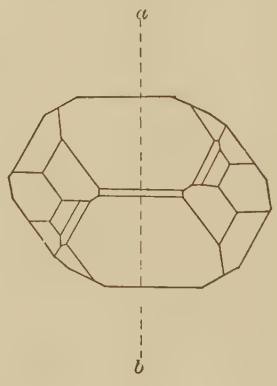


Fig. 8.

crystal which is divided symmetrically by it. In Fig. 8 the line *ab* is the trace of a plane dividing another crystal into equal halves, but it is not a plane of symmetry.

A crystal may possess more than one plane of symmetry in combination with one or more axes of symmetry. In a cube there are three planes of symmetry through the center and parallel to faces of the cube, Fig. 9, and six planes of symmetry passing through the center and diagonally opposite edges, Fig. 10.

One kind of compound symmetry combines rotation about an axis with a plane of symmetry normal to it; another involves a co-

incidence of molecular networks by their translation in a straight line; a third combines this translation with rotation about an axis.

A Crystal Form in crystallography is understood to be all of the planes corresponding to any given symbol which should be present in order to satisfy the symmetry of the crystal. The symbol for a crystal form is the symbol for one face placed in parenthesis, as (210). The number of planes that may be present in a complete form varies from one to forty-eight. Some kinds of forms completely inclose space, others do not. Several kinds may occur in combination on one crystal.

The names given to crystal forms differ somewhat with different crystallographers, as well as the method of designating those that bear the same name, but have different crystallographic positions.

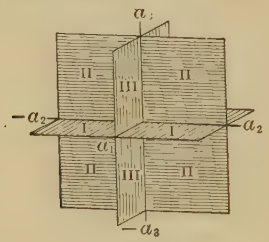


FIG. 9.

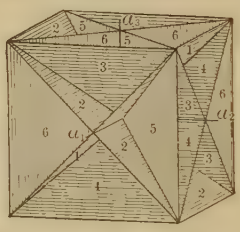


FIG. 10.

The method followed in this book is that of Groth[1] and Federow, and since it has not yet come into general use it is advisable to state it briefly so far as it differs from other methods. It has the advantages of being simple and uniform. The forms may be described in general as follows:

A form is named according to its geometrical shape or character irrespective of its position with reference to the crystal axes, with the exception of dome and sphenoid, two names for the same shaped form:

1. Pedion, a form composed of a single plane.

2. Pinacoid, a form composed of a pair of parallel planes.

3. Dome, a form consisting of two planes intersecting in a plane of symmetry.

4. Sphenoid, a form consisting of two planes intersecting on an axis of symmetry (twofold).

5. Bisphenoid, a form composed of two sphenoids in reversed position on an axis of symmetry, and not parallel; the latter case would be a four-sided prism.

[1] P. Groth. Physikalische Krystallographie. Leipzig, 1895.

6. Prism, a form composed of three or more planes intersecting with parallel traces, in the shape of a prism.

7. Pyramid, a form composed of three or more planes intersecting on an axis of symmetry (threefold, fourfold, or sixfold).

8. Bipyramid, a form composed of two pyramids of the same kind reversed on an axis of symmetry and so placed that they meet one another in one plane, which will be perpendicular to the principal axis of symmetry.

The names of all other forms are those in common use.

The mode of designating the position of pedions, pinacoids, domes, sphenoids, bisphenoids, and prisms with respect to the crystal axes, *a*, *b*, *c*, is as follows:

A form cutting the first axis *a* and parallel to the other two is called the *first* pedion or pinacoid, (100); that cutting the second axis *b* and parallel to the other two is the *second* pedion or pinacoid, (010); that cutting the third axis *c* and parallel to the other two is the *third* pedion or pinacoid, (001).

A form parallel to the first axis *a* and intersecting the other two is said to be *of the first order*—pedion, pinacoid, sphenoid, dome, prism, etc., (0*kl*); one parallel to the second axis *b* only is *of the second order*, (*h*0*l*); one parallel to the third axis *c* only is *of the third order*, (*hk*0); and one intersecting all three axes *a*, *b*, *c* is *of the fourth order*, (*hkl*).

Symbols for Pedions and Pinacoids.

(100), *first* pedion or pinacoid, cutting the first axis and parallel to the other two.

(010), *second* pedion or pinacoid.

(001), *third* pedion or pinacoid

(0*kl*), pedion or pinacoid of the *first kind*, parallel to the first axis and cutting the other two.

(*h*0*l*), pedion or pinacoid of the *second kind*.

(*kk*0), pedion or pinacoid of the *third kind*.

(*hkl*), pedion or pinacoid of the *fourth kind*.

For Domes, Sphenoids, Bisphenoids, and Prisms.

(0*kl*), dome, sphenoid, bisphenoid, or prism of the *first kind*.

(*h*0*l*), dome, sphenoid, bisphenoid, or prism of the *second kind*.

(*kk*0), dome, sphenoid, bisphenoid, or prism of the *third kind*.

(*kkl*), sphenoid, bisphenoid, or prism of the *fourth kind*.

The use of the Miller symbol in conjunction with the name of any form prevents confusion that might arise from differences of usage with regard to the names of forms.

Crystal Systems and Classes.—Owing to difference of usage in regard to the number of systems recognized in crystallography, and to the names used to designate the classes of symmetry, it is advisable to state briefly the method of Groth and Federow followed in this book. Classes of symmetry are designated by the geometrical name of the most general form corresponding to (*hkl*), which is characteristic of each class of symmetry. Beginning with the lowest symmetry the classes and systems are given in order of increasing symmetry, and the corresponding names used by Dana in his text-book are also given for those students who are familiar with these terms. It is to be noted that the Trigonal System is treated by Dana as the Trigonal or Rhombohedral Division of the Hexagonal System, which contains also the Hexagonal Division. The thirty-two classes are called groups by Dana, who also uses the term, type, qualified by the name of a mineral illustrating it. The classes of symmetry represented by the rock-making minerals so far as known are marked by an asterisk.

System.	Class (Groth).	Group, type (Dana).
I. Triclinic	1. Asymmetric or pedial	Asymmetric
	*2. Pinacoidal	Normal, axinite
II. Monoclinic	3. Sphenoidal	Hemimorphic
	4. Domatic	Clinohedral, clinohedrite
	*5. Prismatic	Normal, gypsum
III. Orthorhombic	6. Bisphenoidal	Sphenoidal, epsomite
	7. Pyramidal	Hemimorphic, calamine
	*8. Bipyramidal	Normal, barite
IV. Tetragonal	9. Bisphenoidal	Tetartohedral
	10. Pyramidal	Pyramidal hemimorphic, wulfenite
	11. Scalenohedral	Sphenoidal, chalcopyrite
	12. Trapezohedral	Trapezohedral
	*13. Bipyramidal	Pyramidal, scheelite
	14. Ditetragonal-pyramidal	Hemimorphic
	*15. Ditetragonal-bipyramidal	Normal, zircon

System.	Class (Groth).	Group, type (Dana).
V. Trigonal	16. Pyramidal.	
	*17. Rhombohedral.	Tri-rhombohedral, phenacite
	*18. Trapezohedral.	Trapezohedral, quartz
	19. Bipyramidal.	
	*20. Ditrigonal-pyramidal. . . .	Rhombohedral, hemimorphic, tourmaline
	*21. Ditrigonal-scalenohedral.	Rhombohedral, calcite
	22. Ditrigonal-bipyramidal. .	Trigonotype
VI. Hexagonal	*23. Pyramidal.	Pyramidal, hemimorphic, nephelite
	24. Trapezohedral.	Trapezohedral
	*25. Bipyramidal.	Pyramidal, apatite
	26. Dihexagonal-pyramidal. .	Hemimorphic, iodyrite
	*27. Dihexagonal-bipyramidal	Normal, beryl
VII. Isometric (*Cubical*, Groth)	28. Tetrahedral-pentagonal-dodecahedral.	Tetartohedral, ullmannite
	29. Pentagonal-icositetrahedral	Plagiohedral, cuprite
	*30. Didodecahedral.	Pyritohedral, pyrite
	*31. Hextetrahedral.	Tetrahedral, tetrahedrite
	*32. Hexoctahedral.	Normal, galena

Crystal Habit.—The *habit* of a crystal is its shape, which depends upon the form or forms that have been developed on its surface and the relative sizes of the planes or diameters of the crystal. Thus the habit of one crystal may be cubical, another octahedral; one may be tabular, another prismatic, though bounded by the same crystal forms, as is the case with certain feldspars (Figs. 11, 12, 13, 14). The constancy of habit in crystals of any compound crystallizing under a given set of conditions is remarkable when the many possible positions of planes through a point system of molecules is taken into account, and the simplicity of the forms or combinations of forms that appear on crystals is equally noteworthy for the same reason.

Further, the habit of a mineral differs according to conditions under which it crystallized, though the precise relationship is not definitely known in most cases. Thus potash-feldspar in some occurrences is equidimensional (Fig. 11), in others it is tabular parallel to the second pinacoid (010) (Fig. 12), in others tabular parallel to the third pinacoid (001) (Fig. 13), in still others it is prismatic parallel

to the *a* axis (Fig. 14), in some microlites it is prismatic parallel to the *a* axis and also prismatic parallel to the *c* axis.

Moreover, minerals which appear to crystallize with the same degree of symmetry, and might be expected to develop in crystals of like habit, are persistently different; thus galena is commonly in cubes, less often in octahedrons, very rarely in other forms of the class of symmetry to which it belongs; garnet is commonly in rhombic dodecahedrons, and icositetrahedrons, very rarely in octahedrons, and never in cubes; spinel is almost always in octahedrons, very rarely cubic or dodecahedral.

These differences in crystal habit appear to be in part closely connected with the composition or substance of the crystal, in part

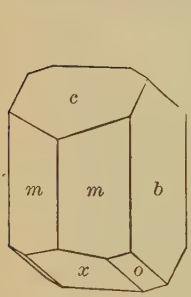


Fig. 11.

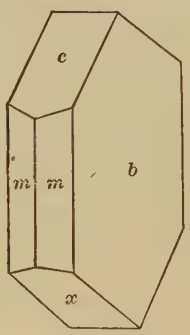


Fig. 12.

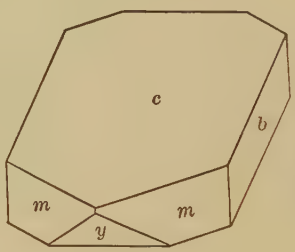


Fig. 13.

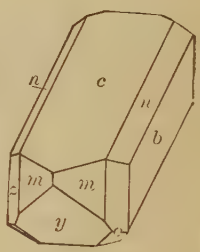


Fig. 14.

dependent on external physical factors. They must therefore be a function of the material of the crystal and its molecular structure, and also a function of the solution out of which the crystal separates—its composition and viscosity, and consequently its temperature, as well as the pressure under which it exists.

Surface Tension.—The separation of a body from a liquid is accompanied by the development of energy along the surface separating the liquid and the body in contact with it, which is known as surface tension. The surface tension of a liquid is a function of its composition and its viscosity. It must, therefore, vary with changes of temperature and pressure. The surface energy of the liquid varies directly as the area of the surface, and is independent of its shape or curvature. Therefore the surface tension or surface energy in a liquid about a crystal is directly proportional to its surface. The separation of a body from a liquid with a minimum expense of energy would, so far as the shape of the body is conditioned by the surface tension of the liquid, result in a form having the least

surface for a given volume of material. This minimum is realized in a sphere, and where the separated body is highly plastic, as a liquid, it assumes a spherical form. But in solid crystals the plasticity is so slight that there is no evidence of molecular distortion that might be due to the surface tension of the surrounding liquid, except possibly in some microlites. However, it is possible to effect a diminution of surface with respect to volume by changing the number of bounding planes and their angular position. Thus in the isometric system a hexoctahedron with forty-eight planes is much nearer a spherical form than an octahedron, and the development of many planes on a crystal, with the truncation of solid angles and edges, may be referable to the influence of surface tension in the liquid from which the mineral crystallized.

Since surface tension becomes a minimum, or zero, when the molecular cohesion in the liquid is the same as its molecular adhesion to the substance in contact with it, and this is dependent on relative masses or densities, it follows that crystals of any one substance, separating from liquids having different relative densities compared with that of the crystal, should exhibit different tendencies toward the development of truncating planes, other conditions being equal; and those crystals should be the more highly modified, or exhibit the greater number of plane faces, which crystallize from liquids whose density differs most from that of the crystal.

The foregoing discussion has proceeded on the assumption that the surface tension between the liquid and crystal is the same on all surfaces of the crystal. This is the case for all planes having like physical properties, that is, for all planes having the same symmetry, for all planes belonging to one crystal form. When the surface tension differs on different planes of a crystal, which must be the case on planes having different physical properties, different symmetry, which belong to different crystal forms, the resulting modification of crystal habit, due to the influence of surface tension, may be understood from the following considerations:

When the surfaces between two liquids and air, or between a liquid, air, and a solid, are in conjunction, as when air, oil, and water, or air, water, and glass, meet, the surface tension between the three pairs being different, that surface which involves the least surface tension increases at the expense of the other two. In other words, that surface is produced which requires the least energy to maintain it. In the cases cited, oil spreads itself between the air and water, and water spreads itself between the air and glass. This

corresponds to what is called capillary attraction. The molecular forces involved are the adhesion of the molecules of one substance to those of another, and the cohesion of the molecules within each substance.

In the case of a crystal those plane surfaces which have different symmetry must consist of molecules differently spaced and differently arranged. They must therefore present different degrees of adhesion or attraction to any given liquid; the surface tension of the liquid on physically or symmetrically different faces of a crystal must be different. Moreover, that plane, or planes, on which the adhesion is nearest in value to the molecular cohesion in the liquid will involve the least surface tension in the liquid, and, so far as the surface tension is the controlling factor in the shaping of a crystal, those planes involving the least surface tension should be developed at the expense of others.

Changes in the composition or physical character of a solution from which a crystal is separating affect the surface tension of the liquid with respect to various crystal faces, since various liquids possess different surface tensions toward crystals of one kind of substance. It follows from this that changes in the character of a liquid may change the habit of a crystal separating from it. And, further, a crystal with a given habit transferred to a different solution, saturated with respect to the substance of the crystal, but possessing a different surface tension with respect to the crystal, may change its habit without change of its volume. Consequently crystals of substances whose density is nearly the same as that of the liquid from which they are separating should be more liable to changes of habit, due to changes in the physical character of the liquid, than those whose density is quite different from it.

A crystal of a given substance, which is capable of separating from a solution of greater density, and which is also capable of crystallizing from a solution of less density, should differ in habit in the two cases so far as the surface tension alone is concerned, and in such a manner that the planes developed upon separation from the liquid of greater density should be those having the greater molecular density, or rather those presenting the stronger attraction toward the liquid; and the planes developed upon separation from the liquid with less density should be those having the lower molecular density, or those presenting the weaker attraction toward the liquid.

Molecular Attraction and Arrangement.—Considering crystallization from the point of view of molecular attraction and movement it is possible to arrive at an understanding of other features of crystal habit than those considered solely in relation to surface tension.

The crystallization of a substance from a solution in which it was previously diffused homogeneously, involves the concentration of the molecules about one or more points within the liquid, that is, their movement or diffusion toward certain centers of crystallization where they become fixed in their position with respect to one another, and definitely arranged in a network or point system.

If the condensed substance is not a crystal, but an isotropic liquid, as when one liquid separates from solution in another upon a change of the temperature to one at which the solutions are no longer miscible, then the diffusion of molecules from the homogeneous solution toward the first separated molecules should be uniform, moving with the same velocity of diffusion in all directions toward the center of attraction. They should be attracted equally in all directions toward the nucleal sphere of separating liquid, because this is physically isotropic, and the physical characters are alike in all directions through it.

It is possible for a crystal belonging to the most symmetrical class of the isometric system to assume an almost spherical shape by developing all of the possible crystallographic forms on one crystal. A hexoctahedron, whose solid angles and edges are truncated by planes of the remaining six forms, would have 146 faces, and would approximate closely to a sphere. When crystals belonging to such a class crystallize from solution, the results of homogeneous diffusion and of the requirements of surface tension in the liquid might be expected to induce the development of crystals with such a spheroidal habit. But the commoner habits for crystals belonging to this class of symmetry are those of cubes, octahedrons, and dodecahedrons. In general, it may be said that instead of highly modified, more or less rounded crystals in any class of symmetry, the commoner habits are cuboidal, bipyramidal, or rather simple forms or combinations of forms. This indicates that there are molecular forces controlling the shape of crystals stronger than those inherent in the solution from which it separates. The controlling factors must exist within the molecule of the crystal, determining the molecular arrangement and the planes bounding the network of molecules.

Consider the possible factors involved in an arrangement of molecules with orthorhombic symmetry, assuming that all of the

molecules are alike physically as well as chemically, as would be the case with a crystal of Mg_2SiO_4, forsterite.

The molecular spacing in three directions, a, b, c (Fig. 15), at right angles to one another, is unequal, and let the molecular distances be $a<b<c$. The molecules attract one another more closely along a than along b, and still less closely along c. Or they attract one another more strongly in one direction than another, which may correspond to different degrees of elasticity in these directions in the crystal. It follows from this that the molecules uniformly distributed in a homogeneous solution must move different distances to unite with the first molecules to form such a crystal, those moving along the line of closest arrangement in the crystal moving farther than those moving along the line of more distant spacing. The resulting aggregation will depend upon several conditions.

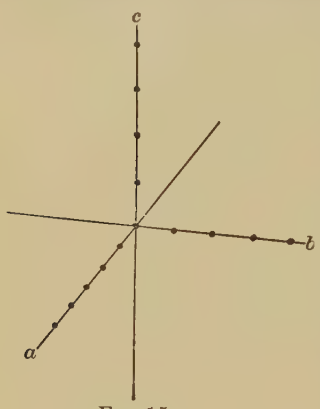


FIG. 15.

If it be assumed that the molecular attraction exerted by the crystal toward the diffusing molecules in the solution has to overcome no resistance exerted by the liquid, and that in a unit of time the same number of molecules arrive along the line a as along b and c, then the velocity of diffusion must be faster in the direction of closer spacing a than in the other directions, b and c.

If there is an infinitesimal resistance within the solution, the faster movement of molecules in the direction a would set up a current, or differential movement, within the liquid solution, which in time would augment so as to increase the supply of molecules in the direction a. The crystal would then increase more rapidly in the direction of the more closely spaced molecules.

An appreciable resistance to diffusion operates to equalize the rates of diffusion or movement along a, b, and c. When the resistance is strong enough the molecules that have farthest to move would not arrive as soon as those that had a less distance to move, that is, more molecules would arrive in a unit of time in the direction of the longest spacing, c; and the crystal would increase fastest in this direction.

It follows from these considerations that changes in the physical character of the liquid from which a crystal separates should affect

the habit of the crystal by modifying the rate of supply of molecules in different directions. It is to be noted that the directions chosen for the crystallographic axes *a*, *b*, *c*, are not necessarily the directions of principal molecular attraction in a crystal, though they may be in most cases.

There is another consideration of the relation between the crystallizing molecules and the liquid solution which is important. It has to do with the relative amount of molecules of the crystallizing substance and of the liquid from which they separate. In any case of crystallization the liquid must be supersaturated with the compound crystallizing from it. But when a comparatively small amount of a substance saturates the solution its molecules must be more scattered when homogeneously diffused than would be the molecules of a compound present in large amount. If the physical conditions accompanying crystallization are alike in the two cases, the substance present in small amount should crystallize more slowly than that present in large amount, the molecules in the first instance having to travel longer distances to unite with one another.

Moreover, the rate of change in the physical condition of the liquid which brings about supersaturation may be so gradual that it seems as though the growing crystal drew the molecules toward it from long distances, as when a single crystal gathers into itself all or nearly all of the molecules of its composition that were in the solution. On the other hand the changes may be so rapid that it appears as though the crystallizing molecules were being hurried or thrown rapidly together, faster in some cases than the crystallizing forces of arrangement can properly dispose of them. This results in the less uniform molecular arrangements known as twins; also in aggregations of many small crystals in various orientations. In extreme cases the resulting concentration of molecules may take the unarranged character of an amorphous jelly, or glass.

Diffusion Currents.—As just remarked, the effect of molecular attractions of different intensities within a crystal network is to set up currents in the liquid following the lines of fastest molecular diffusion. These convection currents play an important rôle in shaping the growing crystal. For the separation of crystallizing molecules reduces the saturation and changes the density of the liquid at the point of crystallization. Moreover, in most cases, the concentration or condensation of the molecules into a crystal liberates heat which raises the temperature of the liquid at that place and farther reduces the saturation.

The stream of liquid does not stop when it reaches the crystal surface but flows on over it, as shown by Lehmann. The effect of this spreading of liquid with reduced saturation is to retard or even prevent the growth of that part of the crystal over which it flows. Any condition, then, which accentuates the difference between diffusion currents approaching a crystal tends to produce acceleration of growth in one or more directions and corresponding retardation in other directions. The fundamental condition that favors differences in the rate of diffusion currents is the viscosity of the liquid. The greater the viscosity, up to a certain point, the greater the differences of velocity in the diffusion currents. Another factor is the rate of supersaturation. The more rapid the change of saturation the more pronounced appear to be the differences in diffusion currents. But one effect of change of saturation resulting from change of temperature or loss of solvent is to increase the viscosity of the liquid, so that the effects of the two factors may be confused.

The effects of currents in a solution which might be produced by forces independent of the molecular forces within a crystal, such as convection currents, if they flowed past a crystal, would supply crystallizing molecules more rapidly to certain sides or parts of a crystal and thus modify its habit. Such effects may seldom be realized in liquid rocks, for the crystals are suspended in the liquid and move with the current, unless they fall at an appreciable rate through the liquid while crystallizing. But of this there is very little evidence discernible in the texture of the rocks, or in the habit of the crystals. Evidence of partial supply of material is found in the case of crystals growing by the side of others that cut off the supply from their side of the growing crystal.

Prolongation of Crystals in One or More Directions.—The effects of different rates of diffusion on the habit of crystals are shown in the dimensions of crystals bounded by regular crystallographic faces, and also in the abnormal shapes of others.

Prismatic Habit.—Normal crystals are often prolonged in a single direction, which is commonly a physically singular axis. This is oftenest the case with crystals that are optically uniaxial, such as apatite, tourmaline, beryl, zircon; but may be the case with crystals that are optically biaxial, as epidote, elongated parallel to the twofold axis of symmetry, *b*; amphibole, augite, less commonly feldspar; these are elongated in one direction which is also the direction of the intersection of two or more planes of cleavage, a physically distinguished direction. This produces a *prismatic* habit. Prismatic

crystals in igneous rocks may be but little longer than wide, or they may be many times longer. Occasionally the length of apatite crystals is three hundred times the width.

Tabular Habit.—Normal crystals are frequently prolonged in two or more directions in a plane, when they acquire a tabular or flattened shape. In crystals with a physically singular axis, as uniaxial crystals, the prolongation in several directions normally takes place in the plane at right angles to this axis, as in melilite, hematite, tridymite. In biaxial crystals the flattening is commonly in a plane parallel to a plane of cleavage, as in mica, gypsum, and the feldspars, which are often tabular parallel to the second pinacoidal cleavage, less often parallel to the cleavages of the third pinacoid or basal cleavage.

It is to be remembered that crystals which may be prismatic or tabular in certain cases may be equidimensional in others, and that one kind of mineral may exhibit different kinds of habit in different occurrences. Thus quartz, which is often prismatic when crystallized in cavities, is commonly equidimensional in igneous rocks. Micas are occasionally prismatic in a direction almost normal to the cleavage, and are sometimes elongated in one direction in the plane of cleavage. Feldspars are sometimes equidimensional, often tabular in one of two directions, or prismatic in one of two directions; one in the direction common to the two cleavage planes, the other at 64° to the plane of principal cleavage

Abnormal Habits.—Hurried crystallization in igneous rocks produced by rapid cooling, when accompanied by increasing viscosity, shows itself in numerous abnormal forms of growth. Similar crystals formed from aqueous and other solutions by rapid evaporation or cooling have been studied microscopically by O. Lehmann [1] and others. Some of the abnormal habits assumed by crystals are illustrated by the following cases:

Prismatic forms due to the rapid elongation of a crystal in one direction become needle-like or acicular, hair-like or trichitic, and fibrous. If flattened, they are blade-like, or ribbon-shaped. They may be nearly straight or curved, and also forked or branched.

Thin prisms are commonly developed from feldspars and other minerals in rapidly cooled rock magmas, either singly or in groups. The most familiar examples are of alkalic feldspars in glassy lavas. The fiber-like prisms may be clustered in nearly parallel bundles

[1] Molekularphysik. Leipzig, 1888. Vol. I, p. 354.

which usually spread more or less at the ends like a brush. Or they may start from the ends of a thicker prism or from the corners of a tabular crystal (Fig. 16). When the spread of the fibrous prisms is great, the cluster assumes a plume-like or spherulitic shape.

Fig. 16.

The curving of thin prisms may be due in part to movements in the viscous liquid, but oftener, probably, to the surface tension of the liquid when opposed by the very slight rigidity or elasticity of the extremely thin crystal. For it has been observed in some crystals forming under the microscope that as the curved crystal became thicker the elasticity of the solid overcame the resistance of the liquid and the crystal straightened itself. In fact the straightening may be so sudden and energetic that the long prism may fracture crosswise. Elastic movements of this kind have been mistaken for evidences of life or of muscular action in growing crystals. Examples of curved crystals in rocks are found in hair-like apatite, acicular pyroxene and feldspar, and in trichites, which may in most cases be pyroxene.

A result of bending and partial fracture by reason of thickening of the prism is to produce spurs or offshoots as in crystals described by Lehmann (Figs. 17, 18). The forking or branching may arise from slightly different orientation of material attaching itself to a grow-

Fig. 17.

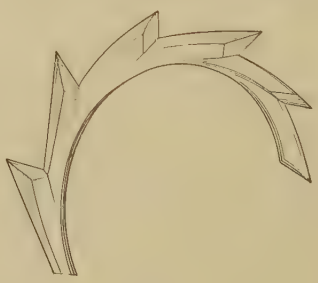


Fig. 18.

ing crystal, or to the elongation of the crystal in another crystallographic direction, which is shown in groups of crystals of augite (Fig. 19) in the lava from Mokuaweoweo and Kilauea, Hawaii,

described by Dana;[1] in the well-known augite aggregates in the pitchstone of Arran (Fig. 20); and in feldspar crystals in obsidian

FIG. 19.—Feather-like forms of Augite: *a* (×35), *b* (×35), *c* (×50) from Mokuaweoweo, *d* (×70) from Kilauea.

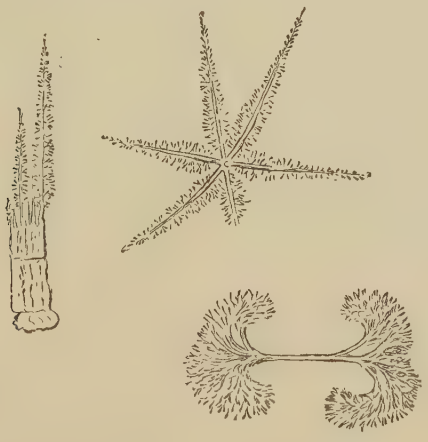


FIG. 20.

in the Yellowstone National Park; in the trachyte of Mt. Rotaro, Ischia,[2] and elsewhere.

[1] Dana, E. S. Petrography of the Hawaiian Islands, in "Characteristics of Volcanoes" by J. D. Dana. 1890. p. 321.

[2] H. S. Washington, Am. Jour. Sci., I, 1896, p. 379.

Tabular forms due to elongation in two or more directions in one plane become extremely thin delicate plates with crystallographic outlines, such as feldspar and mica microlites in volcanic glasses. These may be separate crystals, or groups of subparallel or more or less divergent plates, in feather-like or branching aggregates.

They may be elongated in certain directions and become forked or branched, or built up of more or less crystallographically bounded parts, the most familiar examples of which are the tabular six-rayed snow crystals, which are hexagonal crystals tabular parallel to the basal pinacoid (Fig. 21). Examples of this kind of tabular growth

FIG. 21.

are not common among the rock minerals. They are sometimes developed in hematite, and are occasionally produced in crystals that form in cracks or cleavage planes, as in the case of magnetite and hematite in cleavage cracks of mica.

Equidimensional crystals, especially those in the isometric system as cubes and octahedrons, may be elongated in the directions of the diagonals of the octahedron, or in those of the corners of the cube, or in those of the diagonals connecting opposite edges of the cube, that is, in the directions of the fourfold axes, threefold axes, or twofold axes. The results are complex forms like parallel aggre-

gations of octahedrons and cubes, or more or less symmetrical forms without crystallographic boundary planes. Examples of prolongation in the direction of the fourfold axes are found in some magnetite crystals in glassy basalts, where the branching crystals are composed or parallelly arranged octahedrons, first figured by Zirkel (Fig. 22). An example of prolongation in the other two

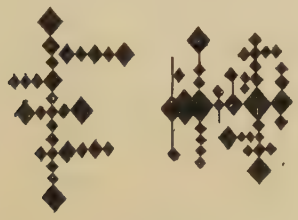


FIG. 22.

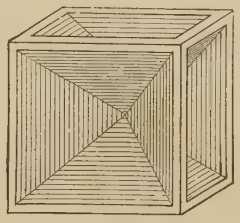


FIG. 23.

directions is furnished by the familiar hopper-shaped crystals of sodium chloride (Fig. 23), in which the growth takes place fastest on the edges and corners of the cubes. Perhaps an example of prolongation in all three of these directions is found in skeleton crystals of leucite, whose crystal habit is icositetrahedral with a salient angle at the end of each of the diagonals mentioned. The abnormal crystals of this mineral in a leucitic lava have been described by Pirsson and are shown in Fig. 24.

FIG. 24.

Irregularly shaped crystals, whose outlines are not crystallographic planes, and whose shape is not referable to crystal symmetry, are produced by extraneous causes, such as convection currents or lack of homogeneity in the surrounding liquid, or to interference from other crystals. The combination of these causes with the diffusion, currents just described results in highly irregular, curved, or angular crystals, such as the olivine in Hawaiian lavas described by E. S. Dana[1] (Fig. 25), *a–g* (×60). Of these, *a–d* are from crystalline basalt, and *e* is from basaltic glass of Mokuaweoweo; *f* is from Maui, and *g* from Kilauea. A somewhat rounded olivine phenocryst from

absarokite, from the Yellowstone Park, is shown in Fig. 25, *h* (×25). Other examples of such irregularly shaped crystals are found in some quartz phenocrysts in glassy lavas; as in hyalorhyolite in the Yellowstone Park (Fig. 26), and in quartz-diorite-porphyry (Fig. 27),

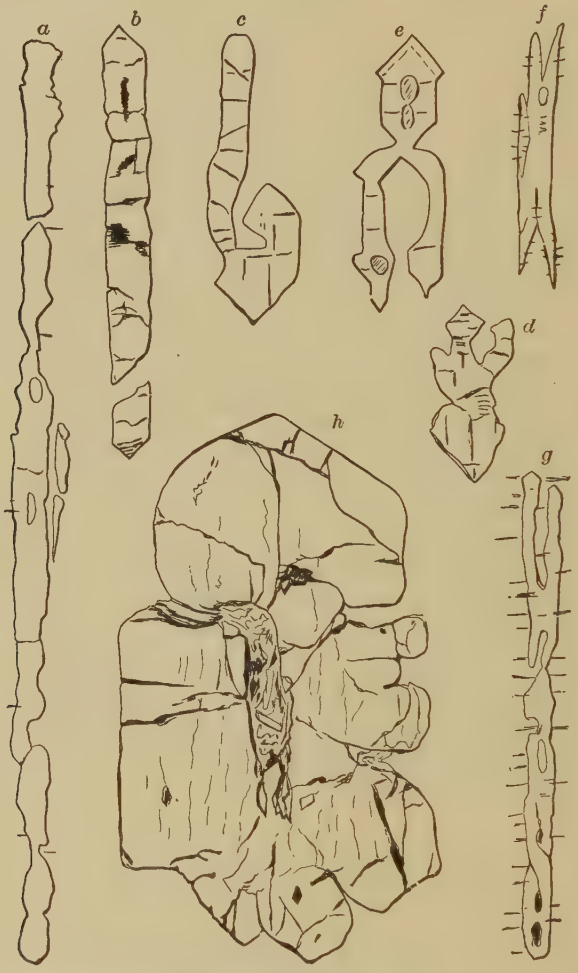


FIG. 25.—*a–g* from basalt, Hawaiian Islands (Dana); *h* from absarokite, Yellowstone National Park.

and in non-porphyritic quartz-diorite (Fig. 28) from Electric Peak in the same region. In the quartz in the glassy rhyolite (Fig. 27) the "bays" or pockets projecting into the crystal from the margin

appear to be incomplete inclosures of the surrounding magma, or glass inclusions in the process of being surrounded by the growing quartz, rather than cavities dissolved out of the quartz crystal owing to some change in the chemical character or temperature of the magma. The similarity in outline to the more or less rounded quartz from the quartz-diorite (Fig. 28), in which there is no question of solution, is significant of the possibility of the production of rounded and irregularly shaped crystals by the act of crystallization under the proper conditions.

FIG. 26.

FIG. 27.

FIG. 28.

Curving forms also result from the dissolving of crystals by the surrounding liquid and are found in some minerals in igneous rocks, especially quartz. But since rounded forms also develop directly upon crystallization, as in the case of some quartzes inclosed in feldspar in certain gneisses, and in the case of some minerals in igneous magmas, as just noted, it is evident that irregular forms produced in each of these ways may be easily confounded. In fact there is no certain method of discriminating in all cases between those rounded forms resulting from crystallization and those due to solution. In many instances rounded crystals described as the result of partial solution or fusion are probably unattacked crystals, whose irregular shapes are those acquired upon crystallization.

Crystals not bounded by crystal faces or planes have been called anhedrons by Pirsson and others. From this usage have sprung the simple adjective terms given below indicating the extent to

[1] Dana, J. D. Characteristics of Volcanoes. New York, 1890. p. 325.

which crystal faces are present on any crystal.[1] These terms and their more cumbersome equivalents are as follows:

Euhedral, well faced, completely bounded by crystal planes, automorphic,[2] idiomorphic.[3]

Subhedral, partially faced, partly bounded by crystal planes, hypautomorphic,[2] hypidiomorphic.[3]

Anhedral, not faced, without crystal planes, xenomorphic,[2] allotriomorphic.[3]

Twinning.—The arrangement of molecules in a crystal is one in which the molecular forces are in equilibrium, at least for the physical conditions under which they come together, and often for a rather wide range of variations in these conditions, as shown by the stability of most rock-making minerals for geological ages. Some pre-Cambrian igneous rocks have existed to present times in an almost unaltered condition But the arrangement in any given crystal is not the only possible position of equilibrium for the molecular forces of attraction. For it is possible in some cases to move them by pressure in certain directions without rupturing the crystal or modifying its physical characters except as regards direction. This ability of the molecules to assume a new position within a crystal is called *gliding*, and the plane parallel to which it takes place in a given instance is called the gliding plane.

From this behavior of a crystal it is evident that there must be more than one possible position of equilibrium in the arrangement of molecules, in which, however, the mutual adjustment of molecular attractions may not be as complete as in the normal crystal. Thus it is possible in the case of a triaxial, asymmetrical arrangement, represented by the network in Fig. 29, in which the molecular attractions in the directions *a*, *b*, *c* are different, for a new molecule to attach itself so that the forces in *a* and *c* are in line and satisfied, but those along *b* are not. A layer of molecules so attached may become the foundation for a properly arranged network of molecules like that first formed, but in a reversed position. The second network, or part of the crystal, bears a definite orientation with respect to the first. The two parts are symmetrically placed across a plane containing the directions *a* and *c*. The orientation of the second part is as though each molecule had been rotated 180° in the plane of *ac* from the position it would

[1] Cross, Iddings, Pirsson, Washington, Jour. Geol., Vol. 14, 1906.

[2] Rohrbach, Min. u. petr. Mitth., VII, 18, 1886.

[3] Rosenbusch, Mikro. Phys. Mass. Gest., p. 11, 1887.

occupy if properly placed in the first network; or as though the second part of the crystal had been rotated 180° about an axis normal to the plane *ac*.

Such an orientation of two parts of any crystal is called a *twinned* position; and a crystal consisting of two such parts is a *twinned* crystal, or *twin*. The plane to which the two parts are symmetrical is called the *twinning plane;* and the axis about which one part may be rotated 180° in order to make it coincide with the other is a *twinning axis*.

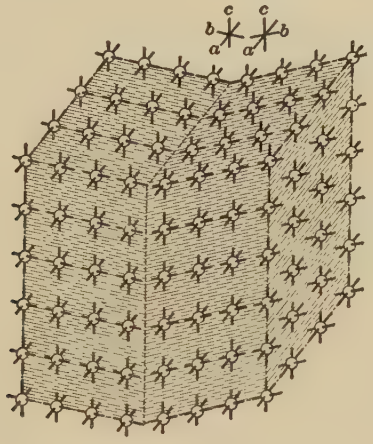


FIG. 29.

No twofold axis of rotation belonging to the symmetry of any crystal can be a twinning axis, because the part of a crystal rotated 180° would coincide with its former position and the physical characters would not differ in direction in the two parts. The same is true of a fourfold and of a sixfold axis of symmetry. Consequently no plane of symmetry perpendicular to a twofold, fourfold, or sixfold axis of symmetry can be a twinning plane.

It follows from this that there may be gliding planes in a crystal which coincide with twinning planes, as in calcite and monoclinic pyroxene, and those which cannot serve as twinning planes, because they are perpendicular to twofold, fourfold, or sixfold axes of rotation in the symmetry of the crystal; that is, the rotated molecules would not sustain a different relation to the stationary ones from that previously sustained towards them. Examples of this are found in halite with gliding plane (110) and ice with (0001) a gliding plane. But it does not follow that all twinning planes are gliding

planes, or rather planes along which gliding may be readily accomplished by laboratory methods. However, the twinning produced in minerals artificially is to be regarded as the same phenomenon since gliding in calcite and augite is accompanied by twinning. And it may be only a question of the degree of ease with which it may be produced. Lamellar twinning in two directions may be produced by pressure in feldspars.

Molecules in coming together in reversed, or twinned, position do not necessarily attach themselves together along the plane of symmetry for their twinned position. They do not necessarily come to a twinned position in any definite plane, but may chance to meet along an irregular surface. The surface along which twinned parts of a crystal are in contact with each other is called the *composition* plane. It is commonly a crystallographic plane, and in some cases is the same as the twinning plane; in others, a different one. Thus gypsum and orthoclase have the same twinning plane (100), but the composition plane in gypsum is (100) (Fig. 30), and in orthoclase is (010) (Fig. 31).

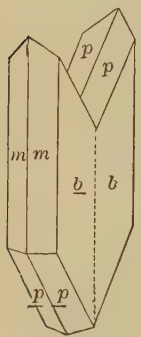


Fig. 30.

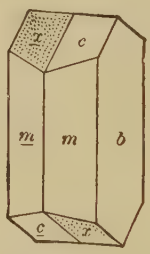


Fig. 31.

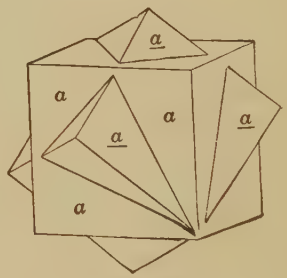


Fig. 32.

The parts of a twinned crystal may be by the side of one another, when it is called a *contact* twin (Fig. 30), or they may lie within one another, when it is a *penetration* twin (Fig. 32). In the latter case the composition plane between the twinned parts is usually quite irregular.

Twinning according to one position, or one *law*, may take place repeatedly in one crystal. When the twinning plane, or axis, is a crystallographic position occurring only once in a crystal form, as a pinacoid or a normal to one, repeated twinning results in parallel layers, or lamellæ, of the crystal in twinned position. This is known as *polysynthetic* twinning, and is best illustrated in the lime-soda-feldspars (Fig. 33). One result of this kind of twinning is seen on

the surface of crystals or on cleavage planes, where the surfaces of the twinned layers, or laminæ, being more or less inclined to one another, reflect light at different angles, and produce a striation of the crystal surface when viewed in incident light. If the twinning plane is a crystallographic plane that occurs more than once in a crystal form as a prismatic or pyramidal face, then repeatedly twinned parts may occur in more than two positions in the crystal, as in the case of rutile (Fig. 34), cordierite, and aragonite.

There may be several different laws of twinning known to occur in one kind of mineral, sometimes in one crystal. The commonest examples are the feldspars, in which three kinds of twinning often occur in one crystal. In these minerals there are five kinds of twinning well known, and others less frequently developed or less definitely established.

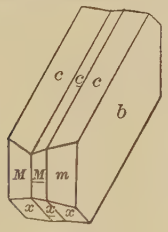


FIG. 33.

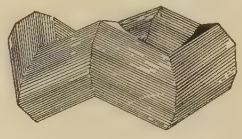


FIG. 34.

Polysymmetry.—In certain substances the typical crystal form approaches so near to that of a crystal with higher symmetry that it may be mistaken at first for one of a more symmetrical crystal. This is *pseudosymmetry,* and is shown, for example, by some triclinic minerals, like the lime-soda-feldspars, in which the angles are nearly those of a monoclinic crystal. In certain orthorhombic crystals the angles are such that the crystals appear to possess hexagonal symmetry. If in addition to this approximation to higher symmetry there occurs polysynthetic twinning in which the laminæ are so thin as not to be visible with a microscope, the submicroscopically twinned crystal exhibits all the physical properties, including outward crystal form, which are characteristic of a crystal possessing the higher symmetry. This is called *polysymmetry,*[1] and is illustrated by orthoclase feldspar, which is undoubtedly submicroscopically twinned microcline. It has been suggested that the orthorhombic pyroxenes, enstatite and hypersthene, may be polysymmetric modifications of monoclinic minerals like diopside.

[1] P. Groth. Chemical Crystallography. New York, 1906. p. 5.

Since twinning in a crystal indicates a less perfect parallelism of the directions of molecular forces than obtains in an untwinned crystal, it follows that any cause tending to hinder the complete orientation of crystallizing molecules will promote the production of twinned crystals. Such causes may be of two kinds: one offering a resistance to the proper rotation of the molecule at the moment of separation from solution, as the viscosity of the liquid; the other preventing the orienting forces from having sufficient time to rotate the molecules completely before they became fixed, as the hurried condensation of rapidly cooling liquids, or the rapid crystallization of highly supersaturated solutions. Consequently, crystals forming from viscous liquids, or those forming very rapidly, are more apt to be twinned, or are more frequently twinned.

Inclusions.—A crystal which has grown with irregular outline, owing to rapid currents, may, if the currents are reduced in rate, tend to fill up the recesses or depressions by slower diffusion, or the crystal may spread from the projecting points and shut in portions of the liquid from which it is crystallizing. The amount or size of such inclusions is an indication of the rate of crystallization at the time of their inclosure. If, upon cooling, the liquid contracts appreciably, it may cease to occupy the whole space and leave a cavity occupied by gas. Or, if it consists of liquids not miscible at ordinary temperatures, it may separate into two liquids and a gas, as is the case with inclusions of water, liquid carbon dioxide, and gas in certain quartz crystals.

When the inclosed liquid contains molecules of the crystal not yet separated, these may eventually crystallize against the walls of the cavity, and may give to it crystallographic faces, producing so-called negative crystals, often developed in quartz, both about inclusions of rock magma, and also about inclusions of water. If the liquid contains other constituents, these may crystallize within it like the transparent cubes within liquid inclusions in some quartzes. Or minerals, such as pyroxene, magnetite, or feldspar, may separate from inclusions of igneous magma, which may for the most part become glass. In some cases, the whole of the inclosed material may crystallize.

When crystals of other substances are present in the liquid, these may be inclosed by the growing crystal. This may be accomplished in some cases without evidence of the inclosed crystals having been moved by the growing crystal; in others, the inclosed crystals appear to have been moved as though they were being excluded from the

growing crystal, when a change of rate of diffusion caused the material to deposit outside of them and shut them in. They are then concentrated in zones or clusters within the larger crystal. Common examples of zones of inclusions are found in feldspars, leucites, and other minerals. This is one form of zonal structure.

When one mineral contains numerous inclusions of other minerals of notable size, which lie in various positions, it is said to be *poikilitic*, or mottled, for, if it possesses noticeable cleavage, the luster of

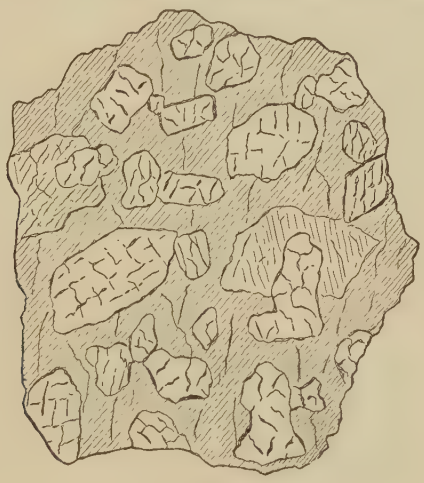


FIG. 35.

the cleavage plane will be mottled by the different surfaces of the inclusions. Fig. 35 represents a poikilitic hornblende section.

If crystals of two kinds of minerals are forming at the same time in a solution, it may happen that they will mutually penetrate one another, so that each will maintain its crystallographic orientation in parts which are irregularly shaped along the contact with one another. The best-known examples of this intergrowth are interpenetrations of quartz and orthoclase or microcline in certain forms of granite. In some cases the quartz assumes more or less definite triangular shapes, which produce a pattern on the cleavage surface of feldspar crystals which has given rise to the term *graphic* intergrowth, or graphic texture or structure (Fig. 36). It has also been called *pegmatitic*, but this term is confusing, because pegmatites are not always composed of minerals intergrown in this manner.

When two minerals are crystallizing at the same time, and one of them exerts an orienting influence over the other, it happens that

crystals of the smaller mass attach themselves to the large crystal parallel to certain directions in it, and, becoming shut in by it, appear as definitely oriented inclusions, often parallel to more than one direction. Such inclusions occur in mica when prisms of rutile lie in the plane of cleavage in directions intersecting at 60°, one of which is perpendicular to the plane of symmetry. Rods and plates, and

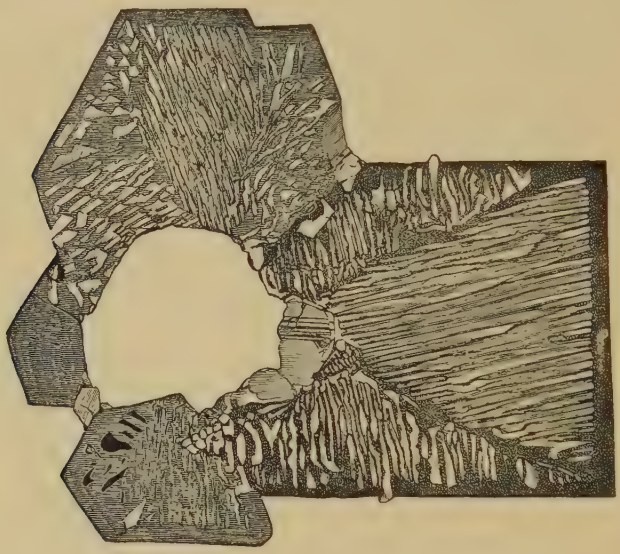


FIG. 36.

grains of what is probably ilmenite, frequently occur as regularly oriented inclusions in hypersthene, augite, and lime-soda-feldspar.

Inclusions shut in at the time of the crystallization of a mineral are called *primary* inclusions. Those that have been introduced or developed in it subsequently are known as *secondary* inclusions.

Secondary fluid inclusions are common in rock-making quartzes. They have been introduced by the healing up of cracks in a quartz crystal through the circulation of water carrying silica in solution. Secondary mineral inclusions arise from solution or decomposition within the original crystal.

Molecular Strain or distortion may occur about a solid inclusion in a rock mineral in consequence of differences in the coefficient of contraction due to cooling. When the inclosed susbtance contracts less than the surrounding mineral, it may exert sufficient pressure within the latter to produce molecular distortion, and anomalous double refraction, or even rupture. Optical anomalies about inclu-

sions are not infrequent in quartz. Actual rupture has been observed about glass inclusions in quartz crystals, as in rhyolite from

FIG 37*a*.

FIG. 37*b*

Eureka, Nev. Fig. 37*a* represents a section of a quartz crystal cut perpendicular to the optic axis. The intersecting cracks are about

glass inclusions, which are shown in section parallel to the optic axis of the quartz in Fig. 37*b*.

When gas has been inclosed in a crystal under great pressure, it may exert sufficient stress against the walls of the cavity, when the crystal has adjusted itself to low pressure, to produce molecular strain and optical anomalies, as demonstrated by David Brewster.[1]

Crystals of Isomorphous Compounds.

Zonal Structure.—When two or more isomorphous compounds crystallize together as a single crystal or a mixed crystal, it usually happens that the proportions in which they mingle vary during the crystallization. The crystal then is not homogeneous, but varies in composition in successive layers or concentric shells, which differ correspondingly in physical properties, those most easily recognizable being color and refraction. A crystal so constituted, when studied in section, appears to be composed of zones of different color or refraction. This is one form of zonal structure. That produced by layers of inclusions is another. It is possible to recognize, in the shapes of successive zones, the habit of the crystal at different stages of its growth. Zonal structure is well developed in the lime-soda-feldspars and, to a less extent, in other rock-making minerals. It will be further discussed in connection with the optical properties.

Segmental Structure or Hour-glass Structure.—Differences in the molecular attractions in different directions in a crystal also show themselves in the constitution of some mixed crystals, or crystals of isomorphous compounds. It appears as though certain molecules in the isomorphous series have a greater tendency to attach themselves in one direction than another, that is, they are more strongly attracted to certain faces of the mixed crystal than to others. The crystal then differs in composition in segments built up of layers parallel to such faces, which may show themselves in differences of color or refraction. In some minerals the segments are pyramidal, with the apexes of the pyramids toward the center of the crystal, and the bases at the surface. In sections of such crystals the reversed pyramids sometimes suggest the shape of an hour-glass, hence the term *hour-glass* structure. The commonest examples of such structure are found in augite in certain basaltic rocks (Figs. 38 *a* and *b*.)

In other cases the segments are not pyramidal, but more or less regularly shaped layers parallel to certain faces of the crystal, as

[1] Edinb. Phil. Jour., 1820, p. 98; 1847, p. 101; 1848, p. 489.

shown in ægirite and acmite in the nephelite-syenites of Norway described by Brögger[1] (Fig. 39, *a*, *b*).

The character of this form of isomorphous crystallization has

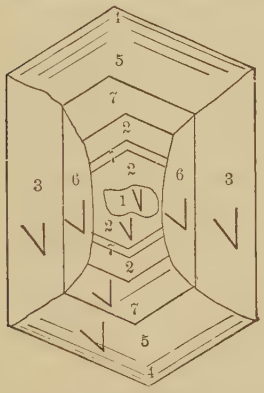


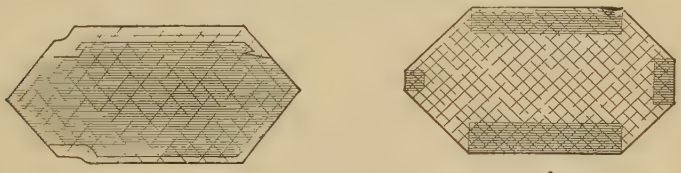
Fig. 38*a*.

Fig. 38*b*.

Fig. 38*a*.—Extinction angles in segments 1, 19°; 2, 31°; 3, 37°; 4, 49°; 5, 50°; 6, 53°; 7, 54° approximately.

Fig. 38*b*.—1, 23°; 2, 26°; 3, 28°; 4, 34°; 5, 36°; 6, 40° approximately.

been investigated by J. Blumrich,[2] and by A. Pelikan,[3] who has also discussed the general question of zonal structure.



a *b*

Fig. 39.

Dissolution of Crystals.—The dissolving of a crystal in a liquid is undoubtedly a process the reverse of crystallization. The molecules at the surfaces leave the solid and pass into the liquid. They may be ionized or otherwise decomposed within the liquid, or may enter into other combination. By reversing the conditions, or process, they may be restored to the crystal, except in certain cases. As crystallization is the building up of a regularly arranged molecular structure, the dissolving of a crystal must be the taking apart of such a structure. It is to be expected, then, that the changes that

[1] Zeitsch. Kryst. u. Min., 16, 1890, pp. 308 and 327.

[2] Tschermaks. Min. u. Petr. Mitt., 13, 1892, pp. 239 and 258.

[3] *Ibid.*, 16, 1896, 1.

take place in the form of a crystal will be somewhat analogous to those involved in its growth, but in the opposite direction, or of a negative character.

Liquid or gas may dissolve a solid without entering into chemical combination with it in the ordinary sense, as the solution of sodium chloride in water; or the dissolution may be accompanied by chemical reaction, as when calcite is attacked by hydrochloric acid. In both cases the effects on the crystal are molecular, and, though the results vary in degree with different solvents and strengths of reagents, they are alike in their general character.

If a crystal be surrounded by a liquid capable of dissolving it, and the liquid be motionless, then the layer next to the surface of the crystal will become saturated with the dissolved substance, unless it diffuse outward into the liquid. If this is the chief factor in the distribution of the dissolved substance, it is evident that there will be more space about angles and edges of a crystal into which the substance may diffuse than opposite a face of the crystal. Consequently, solid angles and edges of crystals should be dissolved more rapidly than the faces, resulting in the rounding of the shapes. Examples of this action are found in certain rounded quartz crystals in igneous rocks, and less often in rounded crystals of other minerals. But it must not be assumed that all rounded crystals are partly dissolved crystals that were previously angular. It is possible for crystals to assume more or less rounded form during the act of crystallization.

It seldom happens, however, that a solution remains motionless while a solid is being dissolved. Changes in the density due to the dissolved substance produce currents which affect the diffusion of the substance in the liquid. Minute currents at the surface of the crystal bring diluter liquid in contact with it, and localize the attack. This results in more rapid dissolution at certain points and the formation of depressions over the surface of a crystal. To some extent these centers of greater activity may be points of lesser resistance in the crystal, due to imperfections of molecular arrangement, for it has been observed in some cases that large crystals, when dissolved, at first develop numerous pits or depressions, and when they become smaller their surfaces are smoother; which accords with the general observation that smaller crystals are oftener bounded by smooth, perfectly plane, faces than larger crystals of the same substance.

Etched Figures.—The solution pits or depressions on the surface of crystals have definite shapes, and are bounded by edges and planes

which have a fixed position with respect to the symmetry of the crystal. They sometimes appear more or less rounded, but this is due to a curved arrangement of minute planes in crystallographic orientation. These definitely oriented depressions are called *etched figures*. They are produced with the sharpest definition when the crystal is acted on by a weak reagent, or for a comparatively short time by a strong one. It is found that the shape of the etched figures varies with the solvent or reagent, and with its strength. It is observed that a crystal dissolves with greater ease in one direction or plane than in another, and that planes that have the same symmetry behave alike toward solvents.

It is also found that the degree of symmetry indicated by the etched figures accords with that expressed by the cohesion of the crystal, especially the hardness. But there is no uniform or direct quantitative relationship between the solubility and hardness of crystals in different directions. It appears from some observations that the softer planes are the more soluble. For example, quartz is more readily dissolved in hydrofluoric acid in the direction of the *c* axis, and it has been found that quartz is not so hard in a plane perpendicular to this axis as in other directions. Calcite dissolves more readily on the basal pinacoid than on a prism face, the ratio being about 1.14:1, according to Spring; and the basal pinacoid is the softer face on calcite.

It is found also, in the case of quartz, that the polarity along the three lateral crystallographic axes, which is shown by its pyroelectrical behavior, obtains for its solubility in these directions. This

FIG. 40.

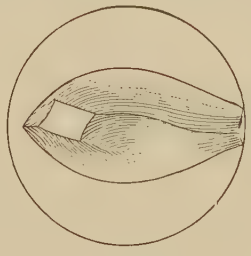


FIG. 41.

FIGS. 40 and 41.—Sphere cut from simple right-handed crystal after being etched by acid for seven weeks: 40, basal view; 41, front view; circle shows original form of sphere, dotted hexagon the position of axes.

is shown by the etched sphere of quartz described by Meyer and Penfield (Figs. 40, 41). The positive pole for falling temperature

was scarcely affected by the hydrofluoric acid during six weeks' exposure, while the negative end was perceptibly dissolved. The sphere was reduced a little more than one half in the direction of the principal axis, *c*.

From this it follows that the shapes and positions of etched figures indicate the symmetry of the molecular arrangement of a crystal, and may be used to determine the degree of symmetry when the outward form of the crystal is not distinctive or indicates a higher degree of symmetry than is actually inherent in the molecular arrangement. For example, euhedral crystals of nephelite are commonly bounded by a hexagonal prism and a basal pinacoid, forms which occur with several classes of symmetry, both trigonal and hexagonal, and might belong to a hexagonal crystal with the highest symmetry. Etched figures on the basal plane are hexagonal (Fig. 42. *a*),

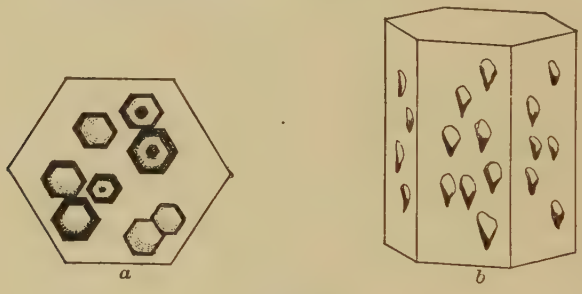


FIG. 42.

but those on the prism faces are unsymmetrical, both with respect to a vertical and a horizontal plane (Fig. 42, *b*). This shows that the two extremities of the *c* axis are not physically alike. The symmetry is therefore pyramidal (hemimorphic). The absence of vertical planes of symmetry, and the like position of the etched figures on adjacent prism faces, show that there is simply a sixfold axis of symmetry: the pyramidal class of the hexagonal system.

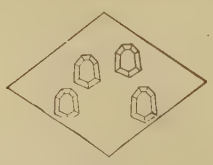


FIG. 43.

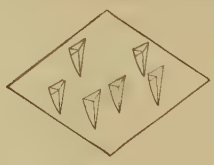


FIG. 44.

The etched figures on rhombohedral faces of calcite and dolomite, produced by dilute hydrochloric acid, show the difference in the symmetry of these two carbonates. Those on calcite (Fig. 43) are

symmetrical to a plane passing through the shorter diameter of the rhombic face, while those on dolomite are unsymmetrical (Fig. 44).

It is to be expected that the etched figures will be different in shape and position on symmetrically different faces of one crystal, and will have the same shape on crystallographically like faces, but not necessarily the same position. This is illustrated by etched crystals of quartz (Figs. 45 and 46), on which the faces of the plus rhombohedron are etched in the same manner, but the positions of the etched figures on the upper and lower faces are reversed, as are also the figures on adjacent faces of the hexagonal prism. This corresponds to the fact that there is a two-fold axis of symmetry at the edges of the prism. The etched figures on the quartz also show the molecular symmetry to be lower than that indicated by the rhombohedrons and hexagonal prism. It is the trapezohedral class in the trigonal system. Moreover, the different positions on the same faces on the two crystals indicate a different molecular arrangement, corresponding to a right-handed (Fig. 45) and a left-handed crystal (Fig. 46).

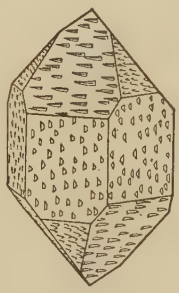


FIG. 45.

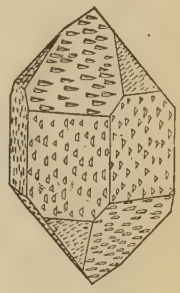


FIG. 46.

Etched figures are characteristic of symmetry and, to some extent, of particular substances, but caution is necessary in making use of them for diagnostic purposes, because of their variation in shape with the position of the surface on which they are produced. For this reason their use in studying rock sections is limited, because the position of the section plane is generally indefinite.

Solution planes.—Those planes in a crystal, in which solution or chemical reaction takes place with greater ease than in others, have been called by Hamberg *solution planes;* and Judd has called attention to the presence of cavities and inclusions in minerals, which appear to have arisen by solution and deposition along such planes while the crystal was under pressure in a rock mass. In some calcite such secondary inclusions occur in the plane of the $-\frac{1}{2}$ rhombohedron $(01\bar{1}2)$, which is the gliding plane. Similar secondary inclusions also occur along irregular planes of fracture or shearing, and it is a question whether the two classes of inclusions can be distinguished from one another. Judd [1] attributes to this source much

[1] Quart. Jour. Geol. Soc., Vol. 41, p. 374, 1887, and Min. Mag., Vol. 7, p. 81, 1887.

of the regularly oriented inclusions in pyroxenes and feldspars in basic rocks—inclusions quite uniform in character, which appear to be titaniferous iron oxide in most cases, and which produce the so-called Schiller in hypersthene, bronzite, and labradorite. But G. H. Williams [1] has shown that these and similar inclusions are in a great many instances primary, having been inclosed during the crystallization of the rock.

Molecular Strength of Crystals.—The molecular strength of a crystal is shown by the resistance it offers to molecular displacement. This resistance exhibits itself in various ways, so that the molecular forces involved appear to be different, or the different modes of resistance are dependent on different factors, namely, the attraction of the molecules for one another, and their arrangement in the crystal, which, however, may be directly dependent on the polarity of the forces of attraction in the molecules.

Elastic Deformation.—When the molecular displacement in a body disappears upon the removal of the force producing it, so that the molecules occupy the same positions they occupied before the force was applied, the deformation of the body is within the limit of elasticity. The amount of elastic deformation in crystals, which may be produced by a given quantity of energy, differs in different directions, according to the symmetry of the molecular arrangement. The amount of elastic deformation or coefficient of elasticity may be determined with respect to changes of temperature, pressure, tension, torsion, or other forms of energy. The forces may be applied equally in all directions, as by uniform change of temperature or by hydrostatic pressure; or they may be applied in definite directions, as when pressure or tension takes place in one direction only.

For the petrologist the importance of the facts of deformation within the elastic limit lies chiefly in the consideration of possible changes in volume of crystals and rocks under various pressures and at different temperatures, that is, in the discussion of the problems connected with the dynamics of rocks. For the petrographer who studies rocks and sections of them at ordinary temperatures and under atmospheric pressure, the forces may be considered normal and approximately uniform. In some instances abnormal, elastic stresses may exist within crystals of sufficient strength to be noted; but the elastic deformation which may have resulted from forces acting at a former time upon the crystals in a rock must disappear

[1] Bull. 62, U. S. Geological Survey, Washington, 1890.

when those forces cease to act, otherwise the molecular displacement was not within the limit of elasticity of the crystal, but belongs to those passing beyond the limit of elasticity, to be discussed in another paragraph.

Perhaps the most sensitive index of molecular displacement within the elastic limit is to be found in the optical characteristics of crystals. The optical indices, sometimes called the *optical constants*, vary with molecular displacement, produced by change of temperature or pressure. Changes in the refraction of air or water due to differences of temperature are familiar to all. The changes which may take place in crystals will be discussed in connection with the description of the optical properties (p. 184). Certain cases of anomalous double refraction, which may be made to disappear on change of temperature, belong to the phenomena of elastic deformation.

For a statement of the behavior of crystals with respect to their elasticity in various directions, so far as they have been investigated, the student is referred to Groth's Physikalische Krystallographie [1] and Lehmann's Molekularphysik.[2]

Permanent Deformation.—When molecular displacement passes beyond the limit of elasticity, but remains within the limit of cohesion, the molecules do not return completely to their original positions. The body sustains a permanent set or strain. When this condition is brought about with considerable ease, the body is said to be plastic; when deformation takes place under the force of gravity, the body is said to be fluid. There is no line of demarcation between a viscous fluid and a plastic solid, and, as all solids are capable of assuming a permanent strain under sufficient stress, there is no line of demarcation between what are called *plastic* and *rigid* solids. A *rigid* body in the ordinary sense may be defined as one which does not sustain an appreciable permanent strain under a considerable load. Since the optical characters of crystals are sensitive indices of molecular deformation, and in many instances most rock-making minerals exhibit little or no optical evidence of permanent molecular strain, it must be concluded either that the rock minerals are quite rigid in the ordinary sense, or that in the cases noted they have not been stressed beyond their limits of elasticity. Experiments on the rigidity of solids have shown that quartz and glass are among the most rigid bodies known; and, though rigidity and hardness are

[1] Loc. cit., pp. 199–221. [2] Vol. I, pp. 41–57.

not identical qualities, there is a sufficiently close relationship between them, so that the hard minerals in general are among the more rigid ones. The hardness of quartz and hard glass is 7 in the scale of Mohs, and the commoner rock minerals are about 6 and 7, so that it may be said that many of the rock-making minerals are distinctly rigid crystals. It is interesting in this connection to note that calcite, with a hardness of 3, is comparatively rigid, while fluorite, with a hardness of 4, is considerably less rigid. There are, however, soft minerals among those forming rocks, whose rigidity is much less than that of quartz. None of them, cons dered individually, would be called plastic, though aggregates of minute crystals, as of kaolin, form plastic bodies—wet clay. The plasticity of such an aggregate is undoubtedly due to the flexibility of the individual lamellar crystals and the slipping of the wet laminæ over one another.

But there are crystals, such as wax, paraffin, and oleate of sodium or potassium, that are distinctly plastic; and certain other organic compounds, which are fluid and exhibit double refraction, are considered by O. Lehmann [1] to be fluid crystals.

Permanent deformation may be homogeneous, that is, it may affect all parts of a crystal alike, so that the physical properties in parallel directions are the same; or it may be heterogeneous, that is, variable through the crystal, limited to certain portions of it, or differing in amount in different places. It may show itself chiefly in the optical properties (p. 187), or may also have affected the shape and outline of the crystal. Permanent distortion of the shape of a crystal is found in curved or bent crystals, such as curved mica and other laminated minerals in some metamorphosed rocks; in curved microscopic prisms and plates of various minerals in glassy rocks, resulting from differential flow in the viscous magma or possibly from surface tension.

Gliding.—The force required to give the molecules of a crystal a permanent set varies noticeably in some cases with the direction through the crystal, there being planes along which the molecules may move with comparative ease without disturbing the continuity of the crystal. Such planes are called *gliding planes*, and, when not planes of symmetry in the crystal, correspond to twinning planes, as already pointed out. This suggests that the movement of the molecules in gliding planes may be one of rotation as well as of translation. Some examples of gliding in crystals are found in the com-

[1] Flüssige Kristalle. Leipzig, 1904.

mon minerals, calcite, ice, halite, monoclinic pyroxene, and cyanite. In calcite the gliding plane is $(01\bar{1}2)$, the plane truncating the polar edge of the unit rhombohedron; in ice it is the basal pinacoid (0001); in halite it is the rhombic dodecahedron (110); in monoclinic pyroxene (001), the basal pinacoid; in cyanite it is (001).

Permanent deformation of crystals in rocks due to gliding is sometimes recognizable in the lamellar twinning in calcite, parallel to $(01\bar{1}2)$, and in monoclinic pyroxene parallel to (001). It is also known in feldspars, both according to the albite and pericline laws.

Fracture and Cleavage.—When molecular strain passes the limit of cohesion in a body it separates or breaks apart. The cohesion of the molecules of a crystal should bear a definite relation to their arrangement and forces of attraction. It is known to bear a symmetrical relation to the elastic properties. When the molecular attractions are the same or nearly the same in all directions, as in glass, the substance should hold together as well in one direction as in another. A rupture or crack should take place with equal facility in all directions. The result is a more or less curved surface, unless there has been some directing force producing it. In the case of glass the curved fracture surface is often like the surface of a shell and is called *conchoidal*. A similar surface is produced in a crystal when the cohesion is nearly the same in all directions, as in quartz.

If the cohesion is different in different directions in a crystal, it will possess one or more minima, or directions in which it is less than in neighboring directions. A crystal should part more easily in the direction of minimum cohesion than in other directions. It should then break more readily in a plane at right angles to such a direction. This ability to part along planes is called *cleavage*. A crystal with cleavage may be split parallel to the cleavage plane at any point in it.

In some cases a crystal is divided into parallel plates in a certain direction, but can not be cleaved at any point parallel to this direction. Such a division of the crystal is called *parting*. It may result from shearing in the rock mass, or from lamellar twinning due to gliding.

Cleavage in crystals may be parallel to a pinacoid, when it occurs in one direction only. If there is cleavage parallel to two or more such planes in a crystal, it differs in perfection or degree on different pinacoids. Pinacoidal cleavage is highly developed in mica and

micaceous minerals, in gypsum, and some of the zeolites. It is pronounced in the feldspars and numerous other minerals.

Prismatic cleavage may be in two planes, or in three. It may occur in more than one direction in one crystal, but the commoner cases are in one direction only. It is characteristic of amphiboles and pyroxenes, and is less pronounced in some other of the rock-making minerals.

Cleavage parallel to three planes having equal physical characters occurs parallel to the faces of a cube, or the faces of a rhombohedron. Cubical cleavage is rare or absent from the few isometric rock minerals, but is well known in galena and halite. Rhombohedral cleavage is highly developed in calcite and the minerals isomorphous with it.

Pyramidal cleavage parallel to four or six planes is rare among the rock-making minerals, but, as octahedral cleavage in the isometric system, is well developed in fluorite.

Dodecahedral cleavage parallel to six planes is sometimes noticeable in the sodalite minerals.

In sections of crystals, cleavage appears as more or less sharp, straight cracks, which are continuous or interrupted according as the cleavage is more or less perfect. It is probably developed to some extent in the preparation of the section, but is also present in some cases before the grinding. So it happens that different sections of one kind of mineral often exhibit quite different amounts of cleavage cracks, according to the orientation of the crystal section. Those cut nearly at right angles to cleavage planes exhibit cleavage cracks when others in the same rock section cut almost parallel to a cleavage plane are nearly free from them. Or it may be said that cleavage nearly normal to the plane of the section will appear as cracks in a section, while cleavage nearly parallel to it will not appear. This is illustrated in Fig. 47, showing a hornblende crystal cut in three directions.

In a section at right angles to the prismatic axis (Fig. 47, *b*), the cleavage cracks are usually numerous, close together, and distinct, intersecting one another at 124°, the plane of the cracks being normal to the section plane. In a section parallel to the second pinacoid (010) (Fig. 47, *c*), the cleavage cracks are fewer, not so close together, and not so distinct as in sections across the prism. The traces of the cracks are parallel to one another, but the planes of cleavage are inclined in two directions, making an angle of 62° with the section plane. In a section parallel to the first pinacoid (100) (Fig. 47, *d*), cleavage cracks are often altogether invisible, if present.

Their traces should be parallel to one another, but the planes of cleavage are inclined only 28° to the section plane, and for this reason are either invisible or are not developed.

In many cases where a crystal is anhedral, cleavage may serve to indicate the crystallographic orientation of the section, or determine whether it belongs to the tetragonal, trigonal or hexagonal system. The inclination of a cleavage crack to the plane of a section may be determined in a general way by focusing a high-power

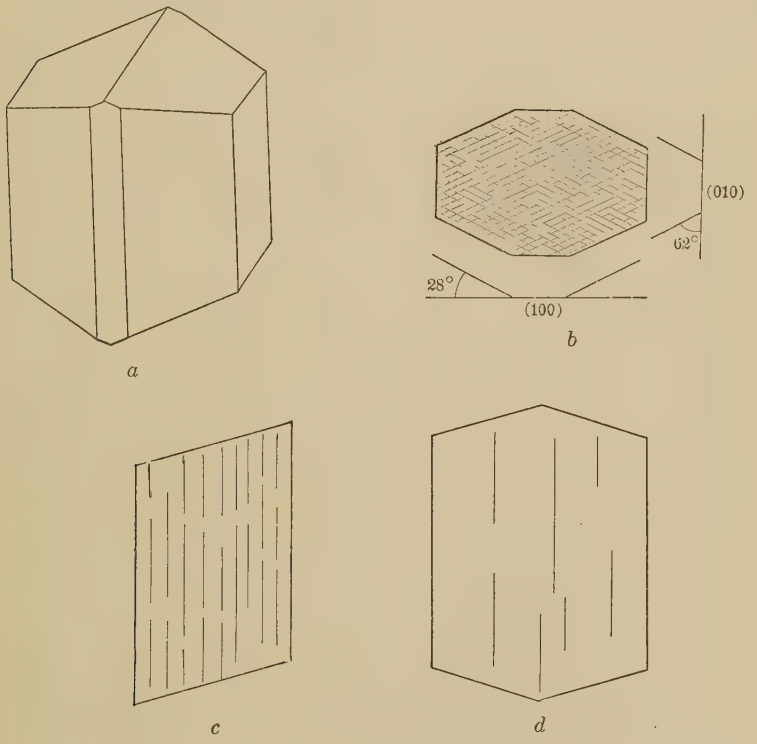


FIG. 47.

lens on the upper edge of the crack, and then upon the lower edge, and noting whether the image shifts to one side or the other, or remains stationary. In the latter case the crack is vertical, or normal to the surface of the section.

Cleavage is an important factor in the megascopic identification of some of the commoner minerals in rocks, such as mica, feldspar, hornblende, and the minerals of the calcite group, and to a less extent of pyroxene.

Hardness.—The hardness of a crystal may be defined as the resistance offered by the cohesion of the molecules to their being torn apart by abrasion. It is sometimes expressed in terms of the resistance to compression, under pressure, of a lens or point applied to a surface of the substance tested. The methods of determining the resistance to abrasion are quite different, and the results not closely concordant. One set of methods is based on the abrasion produced by drawing a weighted point across the surface of a crystal. The hardness is measured by the weight on the point necessary to produce a given effect, or by the force necessary to draw the point or mineral past the other, or by the depth of groove produced under a given set of conditions. Another method consists in boring a depression by rotating a point, and comparing various factors in the process. Still another method consists in grinding a surface with a standard powder, and noting, either the time required to polish it, or the loss of material sustained while a given amount of powder continues to be effective.

Most of these methods yield an average result for a given surface or plane of a crystal. Only that which operates in a given line takes account of differences of cohesion in different directions. Since the cohesion of a crystal varies with direction to an appreciable amount in most crystals, as shown by the cleavage, it is to be expected that the resistance to abrasion will differ in different directions. But it has been demonstrated that there is no direct quantitative relation between hardness and cleavage. For example, in fluorite with pronounced octahedral cleavage, resulting from marked differences in the molecular cohesion in different directions, the hardness is more uniform in different directions than it is in quartz, which has a conchoidal fracture and seldom exhibits cleavage, and in which, therefore, the cohesion is quite uniform in various directions.

There is no definite relation, in general, between the hardness and density of crystals. Thus diamond has a specific gravity of 3.516+ and a hardness of 10, while gold has a specific gravity of 19.33 and a hardness of 2.5–3. However, it may be said that, when one substance crystallizes in crystals with different densities, the denser is the harder. Thus diamond has specific gravity 3.516+ and hardness 10; while graphite has specific gravity 2.23 and hardness 1 to 2. But this is not properly a ratio of 10:1 or 2, for Rosiwal has shown that the ratio is nearer 140,000:1.[1] Aragonite with specific gravity

[1] Verhandl. k. k. geol. Reichsanst., 1896, 475.

2.94 has hardness 3.5–4; calcite with specific gravity 2.713 has hardness 3.

The hardness of a crystal is different on different surfaces, and in some cases it varies with the direction on any one face, and in others with the direction along a given line as determined by Exner.[1] It is not directly related to the molecular cohesion. For example, calcite is harder on certain prismatic planes than on the basal pinacoid. And on the latter it is harder in a direction normal to the trace of the rhombohedral cleavage and toward the rhombohedral face than in the opposite direction. It is also quite different along the two diameters of the cleavage rhomb on the cleavage face; and, parallel to the shorter diameter, it differs according to the direction, up or down.

Marked variation in hardness exists in cyanite. On the first pinacoid (100) it is 4–5 in the direction of the axis *c*, and 6–7 in the direction of the axis *b*; on the second pinacoid (010) it is 7. The crystal may be twenty-four times harder in one direction than in another, assuming the difference between 4 and 7 found by Rosiwal for fluorite and quartz.

Scale of Hardness.—The scale of hardness known as the Mohs scale, which is the one ordinarily used in the description of minerals and is employed in this book, is based on a crude comparison of the hardness of 10 minerals chosen as standards: 1, talc; 2, gypsum; 3, calcite; 4, fluorite; 5, apatite; 6, feldspar; 7 quartz; 8, topaz; 9, corundum; 10, diamond. The numbers 1–10, used in stating the hardness of any mineral, refer merely to the order of the standard mineral which has somewhat similar hardness, and possess no relative quantitative values. The intervals between any two consecutive numbers are very diverse, as is shown by the results of tests made by some of the methods already mentioned. The divergence in the results of these tests is shown by the following statement, the greatest divergence being in the softest mineral tested. The hardness of corundum is placed at 1000.

	Mohs Scale.	Jaggar, 1897.	Rosiwal, 1896.	Pfaff, 1884.
Diamond	10	—	140,000	—
Corundum	9	1000	1000	1000
Topaz	8	152	175	459
Quartz	7	40	120	254
Feldspar	6	25	37	191
Apatite	5	1.23	6.5	53.5
Fluorite	4	.75	5	37.3
Calcite	3	.26	4.5	15.3
Gypsum	2	.04	1.25	12.03
Talc	1	—	.33	—

[1] Preisschrift Wiener Akad., Vienna, 1873.

The determinations by Jaggar were obtained by boring. The instrument, a microsclerometer, is described in the American Journal of Science,[1] together with a statement of other methods and a bibliography of the subject. It is suggested that this method may be applied to crystals in rock sections. The determinations by Pfaff were also made by boring. Those by Rosiwal were obtained by grinding with a standard powder.

Up to the present time the petrographer has made little use of hardness in the determination of minerals, other than by the ordinary tests connected with the Mohs scale. Hardness is a factor in the preparation of rock sections and affects the smoothness or polish of the sections. For, in grinding a section of rock with coarse powder, the soft minerals are more deeply impressed or torn than the hard crystals, and may sustain permanent deformation in spots, or may have minute cavities made in them which are not obliterated by subsequent grinding with very fine powder, so that the soft crystals may have pitted surfaces when harder ones are quite smooth and even. Flexible crystals, like mica, often exhibit permanent molecular deformation, which shows itself in the distortion or crinkling of the laminæ, which is most noticeable between crossed nicols, and is very characteristic of micaceous minerals in thin sections.

Density.—The density or mass of a unit of volume of a crystal of any compound must depend on the mass of the crystal molecule and the number of them in a unit of volume. The mass of a molecule should be some multiple of its molecular weight calculated from the empirical formula. The number of them in a unit of volume of a crystal should depend on the molecular arrangement and the distance between the molecules.

The relative density of crystals, or their *specific gravity*, is expressed in terms of their density as compared with that of water, which is taken as unity. It is determined by finding the ratio between the weight of a given substance in air and the weight of a like volume of water. The methods by which this may be accomplished will be reviewed later on.

That the density of a crystal depends primarily on the density of the elements composing it is shown by comparing the mass of compounds of lead with that of equal volumes of similar compounds of lighter elements. The case is illustrated by the isomorphous series of carbonates and the series of sulphates, with the addition of anhy-

[1] Vol. 4, 1897, p. 399.

drite, which is not isomorphous with the other sulphates, but is somewhat similar. The atomic weights are given in round numbers; the determined specific gravities are approximate.

	At. wt.	RCO_3.	Mol. wt.	Sp. gr.	RSO_4.	Mol. wt.	Sp. gr.
Lead, Pb.	207	Cerussite	267	6.57	Anglesite	303	6.39
Barium, Ba.	137	Witherite	197	4.28	Barite	233	4.49
Strontium, St.	88	Strontianite	148	3.71	Celestite	184	3.97
Calcium, Ca.	40	Aragonite	100	2.94	Anhydrite	136	2.96

It is to be noted, however, that the ratio between the molecular weights and specific gravities in these series of isomorphous compounds is not constant, either for one series or when the series are compared with one another. It is well known that the same substance or compound, when crystallized with different symmetry, has different densities. The following are examples:

Carbon, C	diamond,	specific	gravity	3.516–3.525
	graphite,	"	"	2.09 –2.23
$CaCO_3$	aragonite,	"	"	2.93 –2.95
	calcite,	"	"	2.714
Al_2SiO_5	cyanite,	"	"	3.56 –3.67
	sillimanite,	"	"	3.23
	andalusite,	"	"	3.16 –3.20

In the cases of dimorphism it is sufficient to refer differences of density to differences of molecular arrangement and to the probably different numbers of molecules in a unit of volume, but this is not sufficient to account for the differences in the ratio between molecular weight and specific gravity in isomorphous series, as with the carbonates and sulphates already mentioned, for strictly isomorphous compounds should have the same molecular arrangement and symmetry. However, they may have different spacing of the molecules, which is indicated by the variation in the axial ratios of isomorphous crystals not belonging to the isometric system. If the molecular arrangement were identical in isomorphous crystals and the unit of comparison of the spacing of the molecules in the several minerals (compounds) were the same, then the axial ratios of the isomorphous crystals should bear such a relation to the density of each compound that those crystals with smaller values for the axial ratios should have more molecules to a unit of volume than those crystals with larger values for the axial ratios, since the molecules would be closer together in the first case than in the second. That is, the density should be inversely proportional to the volume and directly pro-

portional to the molecular weight, $d=\frac{m}{v}$. This may be tested by the isomorphous series of sulphates already given. The relation is simplified by considering the volume corresponding to the product of the axial ratios in each mineral, which axial volumes may be assumed to contain the same number of molecules in each case. In the table they follow one another in the order of the size of these axial volumes. The volumes are compared with the ratio of the molecular weight to the density, since $v=\frac{m}{d}$.

	a	*b*	*c*	Axial volume.	*v*	*m*	*d*
Barite, $BaSO_4$	0.81520	× 1 ×	1.31359	= 1.0708;	51.8	= 233 ÷	4.49
Anglesite, $PbSO_4$	0.78516	× 1 ×	1.28939	= 1.0124;	47.4	= 303 ÷	6.39
Celestite, $SrSO_4$	0.77895	× 1 ×	1.28005	= 0.9970;	48.9	= 184 ÷	3.97
Anhydrite, $CaSO_4$	0.89325	× 1 ×	1.0008	= 0.8940;	45.9	= 136 ÷	2.96

From this it appears as though that density, which is relatively higher compared with the molecular weight, since it yields the smaller quotient *v* corresponds to closer molecular spacing; that is, to smaller axial volume. If, however, a similar relationship be sought in the series of isomorphous carbonates it is found to be directly the reverse, as is shown by the following table. But it is to be noted that the order of succession, with respect to the size of the axial volumes, is almost the reverse as regards the series of basic elements when these are compared with the group of sulphate compounds.

	a	*b*	*c*	Axial volume.	*v*	*m*	*d*
Aragonite, $CaCO_3$	0.622444	× 1 ×	0.720560	= 0.44849;	34.0	= 100 ÷	2.94
Cerussite, $PbCO_3$	0.609968	× 1 ×	0.723002	= 0.44100;	40.6	= 267 ÷	6.57
Strontianite, $SrCO_3$	0.60901	× 1 ×	0.72388	= 0.44085;	39.8	= 148 ÷	3.71
Witherite, $BaCO_3$	0.6032	× 1 ×	0.7302	= 0.44045;	46.0	= 197 ÷	4.28

In this statement it would appear as though the density which is relatively higher when compared with the molecular weight, as in aragonite, accompanies larger axial volume, that is, greater molecular spacing; in other words, that the fewer the molecules to a unit of volume the greater the density. This, of course, cannot be true, consequently the premise on which the argument is based must be incorrect. Assuming that these carbonates have exactly the same molecular arrangements in the four compounds, it follows that the unit or standard of measurement of the axial ratios, or of the molecular spacing, cannot be the same in all of these compounds. The axial ratios are established from angular positions of the crystal faces, or

planes of molecules, and do not fix the actual distance of such planes from any point in space. That is, the unit of comparison in the examples just given, $b = 1$, is not the same in all the compounds of an isomorphous series. The spacing of the molecules in the direction of the b axis is undoubtedly different in the crystals of the different compounds in each isomorphous series. This is clearly understood from a consideration of the axial ratio of all isometric crystals, namely 1:1:1. It is not to be supposed that the molecules of all isometric crystals are like distances apart, and a comparison of the densities and molecular weights of various compounds crystallizing with like symmetry in the isometric system shows that there is no fixed ratio between them.

A more definite relation between the density of a crystal, its molecular weight and molecular structure, may be obtained by approaching the subject in a different manner. For if we call the space in a crystal structure occupied by the atoms corresponding to a chemical molecule a *space unit*, then the centers of gravity of these space units form a space grating or network corresponding to the molecular structure of the crystal, and the axial ratios of the crystal or its parameters are proportional to the distances of these space-units in the directions of the crystallographic axes.

Since the space units of the crystals of two different substances contain a chemical molecule of the substance in each case, the mass of each must be proportional to the molecular weight of each substance. The density of each crystal must be proportional to the molecular weight of the substance and inversely proportional to the volume of the space unit, $d = \frac{M}{V}$. From this $V = \frac{M}{d}$ and $V : V_1 = \frac{M}{d} : \frac{M_1}{d_1}$. That is, the volumes of the space units in the crystal structures of different substances are proportional to the ratios between the molecular weight and density in each case. These are known as the *equivalent volumes*, or *molecular volumes* of the substances.[1] The molecular volume is the volume of a space unit of a crystallized substance, which is assumed to have the form of a parallelopipedon corresponding to an element of the network or space grating of the point system of which the crystal is constituted. The volume of such an elemental space unit may be expressed in terms of the edges of the parallelopipedon, χ, ψ, ω, which are proportional to the parameters a, b, c of the crystal. These quantities, χ, ψ, ω, are called the *topic*

[1] P. Groth. Chemical Crystallography, translated by H. Marshall. New York, 1906. p. 39.

parameters. Their determination depends upon the value of the molecular weight of the compound, the accurate determination of the density of the crystal, and on the position and measurement of the crystal forms chosen to fix the value of the parameters of the crystal. A fuller discussion of the subject is to be found in the work on Chemical Crystallography by Groth already cited.

But it is further true that since there are two hundred and thirty point-systems possible that will satisfy the symmetry of the physical characters of crystals, and these may be grouped into the thirty-two classes of symmetry recognized in crystallography, it follows that compounds exhibiting like symmetry and called isomorphous may still possess different molecular arrangements and different numbers of molecules in a unit of volume.

A familiar example of apparent isomorphism, where there is not a correspondence in molecular arrangement of the two salts, is found in the case of calcite, $CaCO_3$, dolomite $(Ca,Mg)CO_3$, and magnesite $MgCO_3$. The symmetry of calcite and dolomite is not the same, while that of magnesite is in doubt, but is probably the same as that of dolomite. Calcite is scalenohedral; dolomite, trirhombohedral. The specific gravity of calcite—2.713—with the heavier molecular weight is less than that of magnesite—3.0–3.12—which has the lighter molecular weight.

The foregoing considerations would seem to be sufficient to account for the lack of a uniform relation between the density of a crystallized compound and its molecular weight.

Density of Isomorphous Mixtures.—If two or more isomorphous compounds crystallize together to form a mixed crystal without condensation or loss of volume, the density of the mixed crystal D should equal the sum of the densities of the several compounds, $d_{,}$, $d_{,,}$ etc., multiplied by the ratios of the volumes of each compound, $v_{,}$, $v_{,,}$ etc., to the volume of the mixed crystal V. That is, $D = d_{,}\frac{v_{,}}{V} + d_{,,}\frac{v_{,,}}{V} + d_{,,,}\frac{v_{,,,}}{V}$, etc., or $DV = d_{,}v_{,} + d_{,,}v_{,,} + d_{,,,}v_{,,,}$, etc. When the volume is expressed in cubic centimeters, $dv = g$, the weight in grams, and $v = \frac{g}{d}$. From this it should be possible to calculate the density of a mixed crystal when the densities and proportions of the components are known. And in cases where only two isomorphous compounds are crystallized together it should be possible to calculate the proportions of these compounds when their densities and that of the mixed crystal are known, for $V = v_{,} + v_{,,}$. This

relation of densities has been found to be true by J. W. Retgers[1] in the case of isomorphous compounds investigated by him.

Determination of Specific Gravity.—Since the volume of any substance differs at different temperatures and the variation is not the same for different substances, the relative densities of crystals vary with the temperature. Accurate determinations of specific gravity should take account of the temperature of the substances compared. However, the variations for the ordinary range of temperatures at which determinations are made are slight as compared with those due to inclusions or impurities in crystals, so that for general petrographical purposes it is not necessary to note the temperature.

It is self-evident that inclusions of other substances, solids, liquids, or gases, affect the determination of the specific gravity of a crystal. Material prepared for specific gravity determination should be as free as possible from inclusions, and those present should be noted both as to kind and amount, and an approximate correction recorded in connection with the observed specific gravity.

Since a solid immersed in water displaces a volume of water equal to its own volume, it follows that the difference between the weight of the solid in air and its weight when immersed in water is equal to the weight of the displaced water, that is, the weight of a like volume of water. The ratio then between its weight in air and its loss of weight in water is its specific gravity. Specific gravity $= \frac{W}{W - w_1}$, when W is the weight in air, and w_1 the weight in water. Since the specific gravity or relative density is a ratio, it is a matter of indifference in what kind of units the values of W and w_1 are expressed, provided they are the same kind in any one case. Consequently, the determinations may be made in units of weight or of length, that is, proportional parts of a scale. Some of the commoner methods of determining specific gravity are the following:

By means of a *chemical balance* a crystal or fragment is weighed in air. It is then suspended by a delicate thread or by a platinum wire, already attached to the balance, and immersed in a vessel of water and again weighed. The wire or support for the crystal should be immersed to the same extent in the water during the first and second weighings, so that the only difference between the weighings is that due to difference in the position of the crystal.

It is, of course, necessary to free the crystal from attached air

[1] Zeitsch. für Phys. Chem., 4, 1889, p. 190.

bubbles. If the solid to be weighed is a porous rock or aggregate of crystals, care must be taken to allow the water to displace the air by absorbing it gradually, as a rapid immersion may imprison air which otherwise would escape. It may be necessary in certain cases to expel the air by heating the water, after which the temperature must be restored to that at which the weighing in air was made.

When the crystals are small or in small fragments their specific gravity may be determined, as suggested by Penfield, by means of a small tube closed at one end (Fig. 48), having a platinum wire fused into the upper end, by means of which it may be suspended from one limb of a balance. The fragments are weighed dry. They are

FIG. 48.

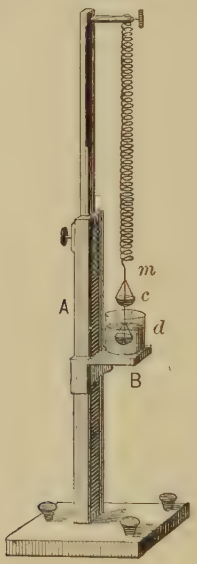


FIG. 49.

then boiled in water to free them from air, and transferred to the tube, which is suspended from the balance, and are submerged in a vessel of water and weighed. The same tube without the fragments is weighed in water as before. This weight subtracted from the weight of the tube containing the fragments gives the weight of the fragments in water. The difference between this and their weight in air is the weight of an equal volume of water, from which the specific gravity is determined.

By means of a *Jolly balance* or spring, shown in Fig. 49, the specific gravity of a crystal may be found with approximate accu-

racy, by noting the stretch of the spring when the crystal is in the upper pan c in air, and also that when the crystal is in the lower pan d in water. The difference between these stretches corresponds to the loss of weight in water ($W - W_1$). The stretch of the spring when the dry crystal is in the upper pan in air is a measure of its weight (W). Specific gravity $= \frac{W}{W - W_1}$. Before commencing the determination the apparatus is adjusted so that the lower pan is in the water and is freely suspended. The position of the spring is noted by observing the reflected image of any point, as at m in the figure. The dry crystal is then placed in the upper pan and the support for the glass containing water is lowered until the lower pan occupies the same position in the water it did before; that is, the same amount of wire should be submerged each time a measurement of the spring is taken. The stretch of the spring is determined by observing the position of the image of the point m on the scale on the upright mirror A. The difference between the two positions of the point m corresponds to the weight of the crystal in air, W. The crystal is then placed in the lower pan and the support B is raised until the pan is suspended in the water at the same depth as in the previous observations. The position of the image of m is noted. This corresponds to the weight of the crystal in water, W_1. The difference between the first and second stretches, $W - W_1$, corresponds to the weight of the displaced water. Specific gravity $= \frac{W}{W - W_1}$. The best results are obtained when the crystal stretches the spring to about the middle of the scale on the mirror.

Pycnometer.—When the crystals are small or in small fragments the specific gravity may be determined by weighing them dry on a chemical balance and also weighing a vessel containing water. The fragments are then placed in the water, all air excluded, the water brought to the same position in the vessel as before and the whole weighed. The difference between the weight of the vessel containing only water plus the weight of the dry fragments and that of the vessel containing water and fragments is the weight of the displaced water. The weight of the dry fragments divided by that of the displaced water is the specific gravity of the fragments.

In order that the water may fill the vessel, or pycnometer, to as nearly the same extent, in both operations, as possible, it is necessary to provide the stopper with a narrow opening. The most sensitive gauge is a capillary tube which may be calibrated, and the value of the units of the scale calculated in grams of water, so that when

the zero-point of the scale is at the middle of the tube the difference between the position of the water in the tube at the time of the two weighings may be taken into account in fractions of grams.

Pycnometers should be as small as possible, in order to reduce the error due to differences in the amount of water at different temperatures. The water should be at the same temperature at both weighings. Any moisture on the outside of the pycnometer should be removed by drying. As small a stopper as possible should be used, owing to the difficulty of placing it at exactly the same level for the two weighings.

In order to remove all air from the fragments, they should be heated in water or placed under an exhaust-pump. It is sometimes necessary to reduce a crystal or rock to minute fragments to free it from inclusions of gas or liquid. But it is to be noted, that extremely minute particles, such as precipitates, appear to have a higher specific gravity than that of larger masses of the same substance. This is accounted for by the condensation of the water at the surface of the solid immersed in it. The smaller the fragments, the greater the surface for a given mass of solid. It is therefore advisable to avoid reducing the size of the fragments beyond what is necessary in order to introduce them into the pycnometer.

Heavy Solutions.—For the purpose of separating two or more minerals having different densities, so that they may be obtained in sufficient quantity for analysis, liquids may be prepared having such density that certain of the minerals may be floated while others sink. Such liquids are known as *heavy solutions*, and may be prepared in various ways, some of which will be described in a subsequent paragraph. The density of a heavy solution may be lessened, by dilution, so that it is possible to reduce it gradually until it is the same as that of any mineral that has a lower density than the maximum for the heavy solution. When this point is reached, a crystal of the mineral will remain suspended in any part of the liquid, without rising or sinking. Since the solid and liquid have the same specific gravity, either may be taken as the indicator of the other. If the density of the crystal is known, that of the liquid is determined by it. Such crystals are called indicators (p. 25), and are used for fixing the density of a heavy solution at a given point. If the density of the crystal is unknown, it may be determined by determining the specific gravity of the heavy solution in which it is in equilibrium. This may be done by means of a balance which measures the buoyancy of the liquid.

The Westphal Balance has been devised for this purpose. It is shown in Fig. 50, and consists of a beam supported at *l* and carrying a glass sinker *r* suspended from *h*. The distance *lh* is divided into ten parts. It is so weighted at the other end that when the sinker *r* hangs in air the pointer may be brought to zero of the scale *s* by leveling the apparatus with the screw *o*. Wire riders are provided, of such weight that the *unit* is equal to the weight of water displaced by the sinker *r* when suspended in it. There are also riders equal to $\frac{1}{10}$ and $\frac{1}{100}$ of this unit. The heavy solution is put in a glass and

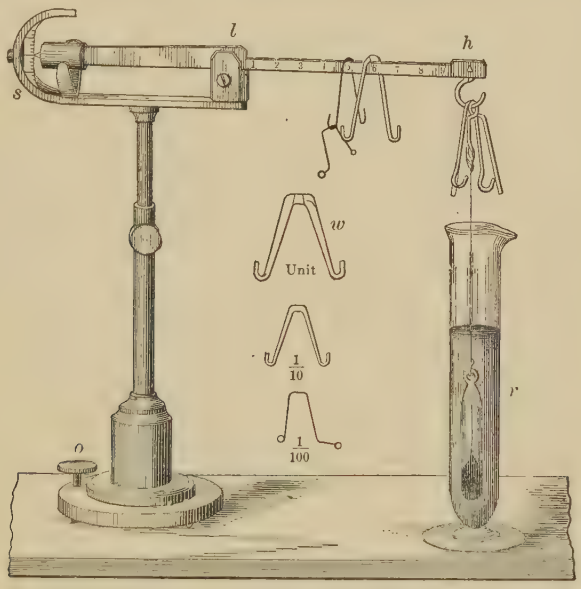


FIG. 50.

the sinker suspended in it, a unit rider is attached to the hook below *h* for each whole multiple of the density of water, and the others are placed on the beam until the pointer is at zero of the scale *s*. In the figure, the riders indicate a density of 2.655, for there are two unit riders below *h*, one at .6, a $\frac{1}{10}$ rider at .5, making .05, and a $\frac{1}{100}$ rider at .5, making .005.

Numerous heavy solutions have been employed, and bear the name of the investigator who first attempted to make use of them or described their characteristics. Only two of them will be described in this connection; the others may be found in Rosenbusch and Wülfing's Mikroskopische Physiographie.[1]

[1] Loc. cit., p. 38.

Sonstadt or Thoulet Solution.—This was the first to come into general use, and has been thoroughly investigated by V. Goldschmidt.[1] It is an aqueous solution of iodide of potassium and mercury, and is very poisonous; its maximum density is 3.196 when prepared in the following manner:

Mercuric iodide and potassium iodide are mixed in the proportion of HgI_2:KI::1.24:1 by weight, with a slight excess of potassium iodide, and are dissolved in cold water, about 500 g. of the salt to 80 ccm. of water. This is evaporated on a water-bath until crystals begin to form, at which density fluorite, having specific gravity 3.18, will float. Upon cooling, the density reaches 3.196, according to Goldschmidt. The solution is stable provided a few drops of mercury are added to it, otherwise iodine separates and darkens the color. When not in use it should be kept from the air.

When mixed in the proper proportions, it may be diluted by the addition of water to any extent and subsequently concentrated by evaporation. Metallic iron decomposes the solution with the separation of mercury. It is therefore necessary to remove metallic iron, by means of a magnet or otherwise, from crystal fragments which have been broken in an iron mortar.

Retgers Solution.—Of several heavy solutions suggested by J. W. Retgers, the best is the liquid double salt, thallium-mercuro-nitrate, $TlHgN_2O_6$, which becomes liquid at 76° C., with a density of 5.3. It is quite fluid and transparent, and may be diluted with water to any extent. It does not attack metallic sulphides. The apparatus in which this solution may be used is described on p. 28. Numerous other solutions have been investigated by Retgers,[2] but that just mentioned is the densest, and does not react on the sulphides of the metals which may occur in rocks.

Other solutions which may be found described by Rosenbusch (loc. cit.) are: Klein's[3] solution of cadmium borotungstate in water, having a maximum density of 3.6; Rohrbach's[4] solution of barium-mercury-iodide, with a density of 3.588; Brauns's[5] solution of methylene iodide, CH_2I_2, density 3.33; and others.

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[1] Neues Jahrb. Min., etc., B. B. I., 179, 1881.

[2] Neues Jahrb. Min., etc., 1896, I, 212–221, and II, 183–195.

[3] Comp. Rend., 93, 318, 1881; Bull. Soc. Min. Fr., 4, 149, 1881; and Geol. Mag., 8, 273, 1891.

[4] Neues Jahrb. Min., II, 186, 1883.

[5] Ibid., II, 72, 1886.

CHAPTER III.

OPTICAL PROPERTIES.

Introduction.—The physical characters of crystals which show a much higher degree of symmetry than exists in the molecular arrangement, and yet are in certain classes of crystals definitely related to the molecular structure, embrace the optical, thermal, electrical, and magnetic properties of crystals, so far as concerns radiation and conductivity. The electrical behavior of certain crystals upon changes of temperature or of volume—pyroelectricity and piezoelectricity—exhibit much lower symmetry than that of electrical radiation and conduction.

While all of these characters are of fundamental significance in the comprehension of crystals, the optical properties are much more easily studied, and serve as a ready means of identification of most rock minerals. For this reason, and because the optical methods of investigation of minerals are chiefly employed by petrographers, especially the microscopical study of thin sections of rocks, the optical properties of crystals are discussed in considerable detail in this book. The other properties will not be described in this connection, as they have not as yet come into use petrographically.

In order to employ intelligently the methods of optical investigation applicable to a study of rocks in thin sections, it is necessary to have in mind the fundamental principles of the undulatory theory of light and to understand the special application of these to the optical phenomena of crystals. For this reason it is advisable to present a brief review of those essential features of the undulatory theory of light that bear directly upon the optical phenomena of crystals, especially their behavior in polarized light.

Light is a form of energy which may be considered to be transmitted as undulations or waves in the ether pervading all things. The mode of transmission of these wave motions in amorphous and in crystallized substances is the subject that chiefly concerns petrog-

raphers. To understand wave motion it is necessary to begin with simple harmonic motion and recall the definitions of several terms which are frequently used in the discussion of the phenomena in question.

Simple Harmonic Motion.—The uniform motion of a particle in a circular path when projected on a diameter of the circle becomes the motion of a regular oscillation or vibration in a straight line, and corresponds to what would take place if a particle of an elastic medium at rest were displaced by a force imparting to it a velocity which decreased with the distance of displacement until it became zero, at which moment the particle would be drawn back with increasing velocity until the initial point was reached, when the acquired velocity would carry the particle in the opposite direction and the displacement would take place in the opposite manner to that first described.

The character of this motion will be understood from Fig. 1. A particle moving uniformly from A to E in the circle will traverse equal distances AB, BC, etc., in equal times. When projected on the diameter EE' the distances ab, bc, etc., are traversed in equal times, the initial velocity at a in the direction aE being the maximum. The velocity at a, the center, is equal to that at A on the circle, the paths being parallel.

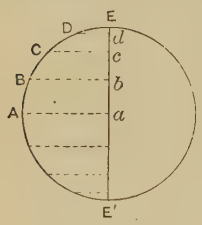

FIG. 1.

The motion back and forth along the line EE' with regularly varying velocity is *simple harmonic motion*, or periodic vibration.

The *amplitude* of the motion is the distance aE or aE', that is, the distance from the median point to that of the end of the swing. In the case of light vibration the strength of the light or its intensity is proportional to the square of the amplitude.

The *period* of vibration is the interval of time which elapses between the passage of a particle from a given point to its next passage from the same point in the same direction.

The *phase* of the motion is a fraction of the period reckoned from some given point taken as the origin of the motion. It is the practice to call the motion in one direction from the median point of maximum velocity *plus*, that in the opposite direction being *minus*.

Wave Motion.—When a simple harmonic motion or vibration is compounded with a uniform motion in a direction at right angles to the line of vibration the resultant motion will be a *harmonic curve*

or *wave form*, such as shown in Fig. 2. Wave motion of this kind in a plane may be considered as produced by a vibration in a line EE' at right angles to the linear direction of transmission, EPR, of the wave. The upper point of maximum displacement, P, is called the crest, the lower point, Q, is called the trough, of the wave. The distance from any point, P, to a corresponding point, R, on the next wave is a wave length λ.

Two waves are in the same phase when they are at corresponding points of their vibrations. Thus when one is at the crest the other is at its crest, etc. Two waves differ by half a wave length, or have a phasal difference of one half λ, when their vibrations are similar but in opposite directions. Thus, when one is at the crest the other

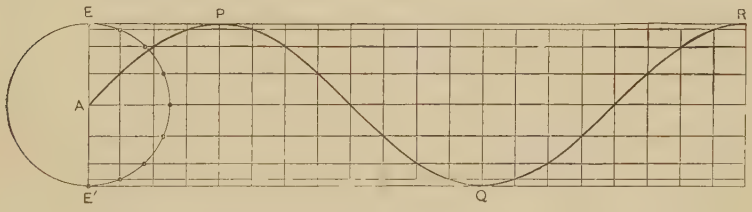

FIG. 2.

is at the trough. When one has plus motion the other has minus motion.

Ether waves of different lengths (λ_1, λ_2, λ_3, etc.) give rise to different colors of light or heat. For violet light at one extreme of the spectrum the wave length (λ_v) is about 0.000380 mm. while for red near the other end the wave length (λ_p) is about 0.000760 mm. That is, $\lambda_p = 2\lambda_v$, approximately. The velocity of transmission of light of all kinds of wave lengths is the same in vacuum, but in any medium the velocity of transmission varies with the wave length. There is, therefore, one velocity for violet and another for red light.

Since waves of all kinds of light traverse space with the same velocities but have different wave lengths, the periods of vibration must be different; the shorter waves corresponding to shorter periods of vibration.

Wave Surface.—If wave motion be produced at a point in space it will be transmitted in all directions from the point outward, and will proceed at the same velocity in all directions; consequently, at a given time all points in like phases of vibration will be equally distant from the point of origin, that is, they will lie on surfaces of spheres concentric with the point of origin. The surface at which

the wave motion is in like phase is called a *wave surface* or *wave front*. In the case described the wave surface is spherical. If the wave motion proceeded from many points situated on a plane surface it would be transmitted in many spherical waves, having a common tangent plane parallel to the surface in which the motion originated, and the resulting wave surface would be a plane. If the wave motion was transmitted with different velocities in different directions and the variations were gradual the wave surface would be a warped surface of some sort.

In Fig. 3 the circle represents the cross section of a spherical wave surface, in Fig. 4 the ellipse represents the section of an ellip-

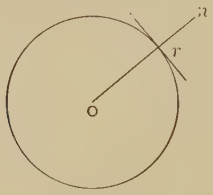

FIG. 3.

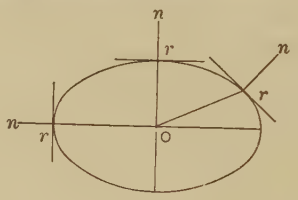

FIG. 4.

tical wave surface. The direction, or line along which the wave motion appears to have traveled from *o* to reach any point *r* of the wave surface, has been called a *ray*, which is a useful conception for the construction of diagrams and the discussion of light phenomena. The plane surface at the extremity of a ray at any point on a wave surface is called the *ray front*. With warped surfaces the ray front at any point is the tangent plane at that point. The *normal* to the ray front is a line perpendicular to it.

In Fig. 3 it is seen that the ray front is at right angles to the ray, and the normal *rn* is in the direction of the ray. While in Fig. 4, an elliptical surface, the ray front is not at right angles to the ray except at the extremities of the major and minor axes of the ellipse. Likewise the normal *rn* to the ray front is not in the direction of the ray, except in the directions of the principal axes of the ellipse.

Media in which wave motion is transmitted with equal velocities in all directions are called *isotropic*. They include gases, most liquids, unstressed glasses, and unstrained crystals of the isometric system. Media in which wave motion is transmitted with different velocities in different directions are called *anisotropic*. They include stressed glasses and all crystals except unstrained ones in the isometric system.

Reflection.—When wave motion proceeds from one medium to another it generally happens that from the surface of contact between

the two media there proceed two wave motions, one forward into the second medium, the other backward in the first. The latter is said to be reflected from the surface of the second medium.

The resultant wave motion may be shown by the accompanying Fig. 5 for the simple case of isotropic media. Let us consider the case of plane faced wave motion, corresponding to that of a beam of parallel,

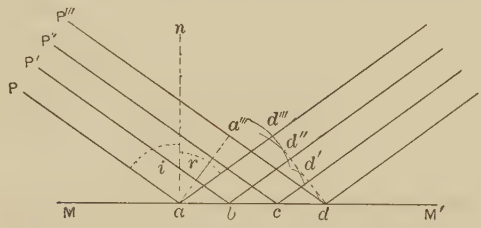

FIG. 5.

monochromatic light. Let P, P', P'', etc., be the parallel rays of such a beam; MM' the surface of the second medium. When the ray P reaches the surface MM' the wave front will stand at aa'''. The wave motion along the line Pa that is reflected back in the first medium will start from a with the same velocity as it had before impact, since the medium is the same. In like manner, for each of the parallel rays P', P'', P''', when each reaches the reflecting surface, it will return with the same velocity as before. At the moment when P''' has reached d the wave motion along Pa will be somewhere on a sphere whose radius is equal to the distance $ad''' = a'''d = vt$, the distance traversed at the velocity v of the wave motion in the time t elapsed since Pa reached the surface MM'. The motion along $P'b$ will have reached the surface of a sphere whose radius is $bd'' = b''d$, and that along $P''c$ will be on a spherical surface whose radius is $cd' = c'd$. The points b'', c' may be found on $P'''d$ at the intersections of lines from b and c parallel to aa'''. Similarly for all the parallel rays of the beam; consequently, the wave front will be a plane tangent to all of these spherical surfaces, and will cut the plane of the diagram containing the rays P, P', P'', P''', in the line dd'''. The ray whose front is at d''' is ad''' which is therefore the reflection of Pa.

Erecting a normal at a, the angle Pan is the angle of incidence i, and nad''' the angle of reflection r. These are equal, since both the triangles $aa'''d$ and add''' have a right angle, a common hypothenuse, and the sides $a'''d$ and ad''' equal, therefore the angles daa''' equals the angle add''', and $daa''' = Pan$ and $add''' = nad'''$. That is,

$nad''' = Pan$, $r = i$. The angle of reflection is equal to the angle of incidence. The reflected ray and incident ray are in the same plane as the normal to the surface when the medium is isotropic.

When light is reflected from a surface the amount reflected relative to the amount of incident light varies greatly according to the relative density of the two media, the angle of incidence and certain qualities of the media depending on their molecular elasticity. This gives rise to the character called the *luster* of a crystal.

Refraction.—When wave motion is transmitted from one medium to another it progresses in the second with a different velocity depending on the relative densities of the two media. The velocity of transmission varies also with the wave length—color of the light. In an isotropic medium the velocity for any given color is constant in all directions. When a wave motion passes from one isotropic medium into another its direction of transmission is changed with its velocity and according to the angle of incidence at the surface

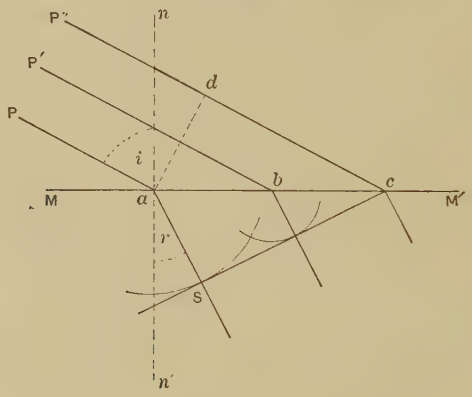

Fig. 6.

of the media, as is shown in Fig. 6. Let a beam of parallel rays P, P', P'', etc., meet a second medium at an angle Pan. Let v be the velocity of transmission in the first medium and v' the velocity in the second medium. When the ray Pa has reached the surface MM', the wave front is at ad. When the ray $P''c$ has reached the surface MM', the ray Pa will have advanced in the second medium a distance as proportional to the relative velocities in the second and first. For if $dc = vt$ and $as = v't$, when the times are equal $\frac{dc}{v} = \frac{as}{v'}$, $\frac{dc}{as} = \frac{v}{v'}$. The ray front for Pa will be somewhere on a sphere whose radius is as. The same will be true for all intermediate parallel

rays. The wave front within the second medium will be a plane tangent to all the spheres from a to c, the latter being zero at the moment when P'' reaches the surface MM'. Since the second medium is isotropic the ray front is at right angles to the ray and the direction of the continuation of the ray Pa within the second medium will be found by connecting a with the point of tangency s of the wave front with the sphere about a, that is, as. The direction of the ray Pa has been changed or *refracted* on entering the second medium. The angle of refraction is measured from a normal nn', and bears a constant ratio to the angle of incidence which appears from the triangles acd and acs. Each is a right-angle triangle, with common hypothenuse ac. In these

$$dc = ac \sin dac = ac \sin Pan = ac \sin i,$$
$$as = ac \sin acs = ac \sin san' = ac \sin r,$$

where i is the angle of incidence, Pan, and r the angle of refraction, san'. But $\frac{dc}{as} = \frac{v}{v'}$ when v is the velocity of transmission in the first medium and v' that in the second. Hence

$$v = ac \sin i \quad \text{and} \quad v' = ac \sin r,$$

ac being alike,

$$\frac{\sin i}{v} = \frac{\sin r}{v'} \quad \text{or} \quad \frac{\sin i}{\sin r} = \frac{v}{v'} = n, \text{ a constant.}$$

That is, the sine of the angle of refraction bears a constant ratio to the sine of the angle of incidence, the ratio being the same as that between the velocities of transmission in each medium.

The velocity of transmission of light waves is less, the denser the medium. Therefore, when light passes from a rarer to a denser medium, the ratio $\frac{\sin i}{\sin r} = \frac{v}{v_1 < v}$ is greater than unity, the angle of incidence is greater than that of refraction, and the refracted ray is bent toward the normal. When light passes from a denser to a rarer medium, the ratio $\frac{\sin i}{\sin r} = \frac{v}{v_1 > v}$ is less than unity, the angle of incidence is less than that of refraction, and the refracted ray is bent away from the normal (Fig. 7).

The constant $n = \frac{\sin i}{\sin r} = \frac{v}{v'}$ is called the *index of refraction* when one of the two media is used as a basis of comparison. In most

cases the medium chosen as a standard is air. In isotropic media the *index of refraction* varies with the wave length of the light transmitted, but for a given wave length is constant for all directions in a given substance, and is characteristic of the substance. The relation between the index of refraction and the wave length is expressed very nearly by the equation $n = A + \frac{B}{\lambda^2}$, when A and B are constants peculiar to each substance. From this it is seen that the value of n increases as that of λ decreases. That is, the smaller the wave

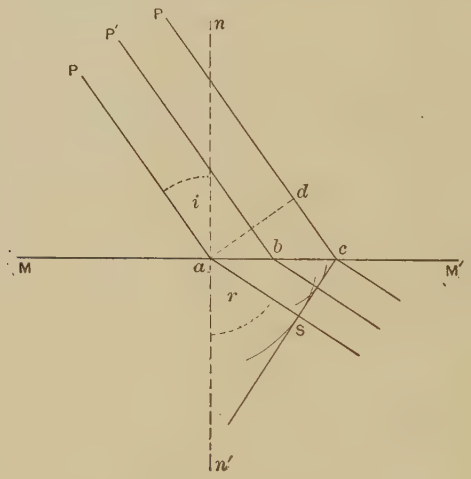

FIG. 7.

length, the larger the index of refraction, which, therefore, is larger for violet light than for red.

When white light enters an isotropic medium, the violet rays have smaller angles of refraction than the red. They are bent nearer to the normal and are more strongly refracted. This leads to a dispersion of the component wave motions of white light, and the production of the colors of the spectrum in the well-known order of arrangement, from red, through orange, yellow, green, blue, to violet.

Critical Angle—Total Reflection.—When wave motion passes from a denser to a rarer medium, as already said, the angle of refraction is greater than the angle of incidence, $\frac{\sin i}{\sin r} < 1$. It follows that, as the angle of incidence increases in values, there is a position in which the angle of refraction becomes 90° before the angle of incidence

has reached that value. Light impinging upon a surface at this particular angle would not enter the second, rarer medium, but would pass parallel to its surface. This angle of incidence is called the *critical angle*. If the angle of incidence becomes greater than the critical angle, the light will be *totally reflected* from the surface. When the angle of refraction, r, is 90°, $\sin r = 1$, and $\frac{\sin i}{\sin r} = \frac{v}{v'}$ becomes

$$\sin i = \frac{v}{v'} = n.$$

The values for n, the index of refraction, as determined for solids and liquids and as used for crystals and glasses, are given with respect to air, when light passes from a rarer into a denser medium. In the expression for the critical angle, $\sin i = n$, the value of n is the reciprocal of that used as the *index of refraction*, since for the critical angle light passes from the denser to the rarer medium. Therefore, the critical angle of any crystal or glass with respect to air may be found from the expression $\sin i = \frac{1}{n}$, in which n is the *index of refraction* of the substance.

Application.

The phenomena of reflection, refraction, and total reflection find various expressions in the optical study of minerals and their inclusions, both when observed with the unaided eye and when studied microscopically.

Lenses.—The refraction of light by isotropic media finds its most important application in the construction of lenses of glass for magnifying minute objects, as well as in the form of the lens of the eye and its relation to the retina and to sight. A few principles necessary to the understanding of the construction and use of the microscope should be reviewed in this place.

A simple lens is constructed of homogeneous, isotropic material, commonly glass, in such a manner that its surfaces are spherical curves of various curvatures. In certain lenses one side is a plane.

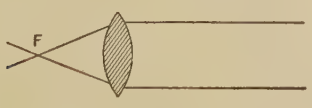

FIG. 8.

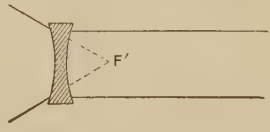

FIG. 9.

For every thin-edged lens there is a *real focus*, F (Fig. 8), at which all rays from a beam of parallel rays converge. There is a real focus

on each side of the lens. These are not at the same distance from the lens, except when the two surfaces have the same curvature in opposite directions. With thick-edged lenses, the rays from a beam of parallel light diverge upon passing through it and converge toward the side from which the light enters. This is called a *virtual focus*, as at F' in Fig. 9.

From Fig. 10 it is evident that, if F is the real focus of a lens, rays passing from a more distant point, O, through the lens will not

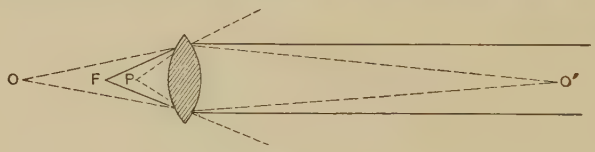

Fig. 10.

become parallel, but will converge to some point, O', while those from a less distant point, P, will diverge upon leaving the lens. From this it is evident that an object at a greater distance than the real

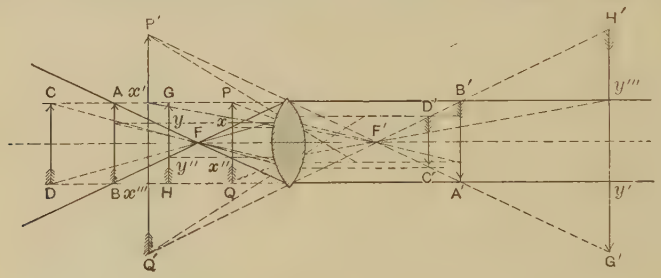

Fig. 11.

focus will yield a *real* image (Fig. 11) on the other side of the lens, which will be inverted and will be the same size, $A'B'$, as the object when the distance is twice that of the real focus, as AB, but will be smaller, $C'D'$, when the distance is greater, as CD; and will be larger, $G'H'$, when the distance is less than twice the distance of the real focus, as GH. If the object is nearer the lens than the real focal distance, as PQ, the diverging rays will yield a *virtual* image, $P'Q'$, which will be larger than the object.

Compound lenses are constructed of two or more simple ones, so shaped as to correct the distortion necessarily produced by lenses with spherical surfaces, spherical aberration, and to obviate the difficulty of preparing properly curved ellipsoidal or hyperboloidal ones. They are sometimes also constructed of several different kinds

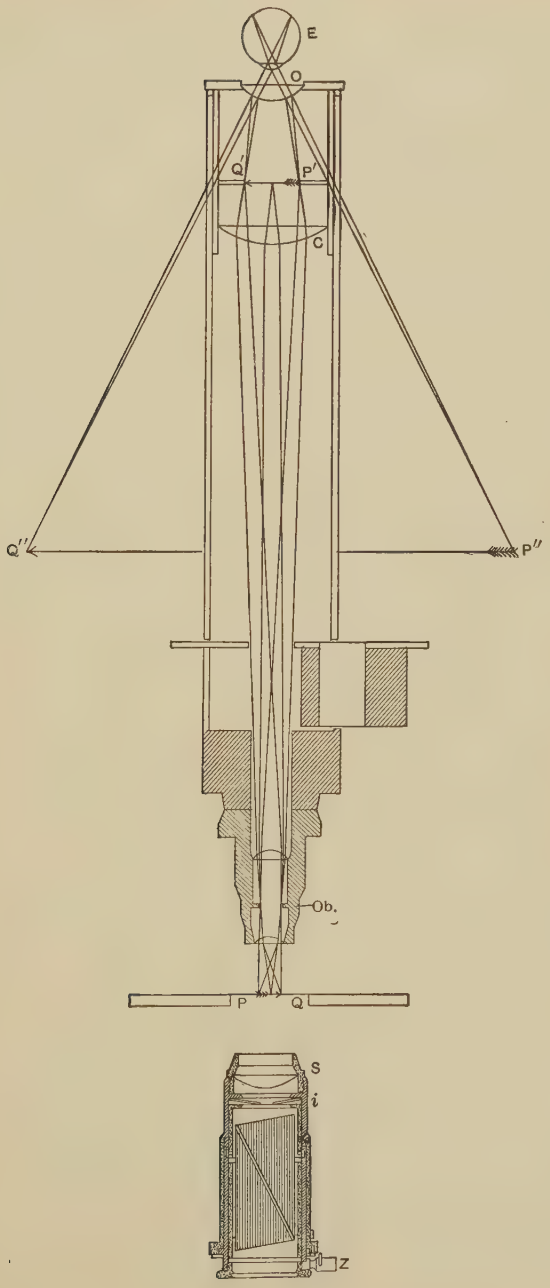

Fig. 12.

of glass, in order to counteract the different degrees of refraction for different kinds of light, chromatic aberration, which obtains in any given isotropic medium. They may also be arranged with special reference to producing an image with a particularly thin focal plane, or, in other cases, with considerable depth to the focal plane, furnishing greater penetration.

Microscope.—Combinations of lenses are used, as in the microscope, in order to transform a real image of moderate size into a much larger virtual image, thereby magnifying the object to a considerable extent. The combination ordinarily used in a petrographical microscope is shown in Fig. 12, which represents a diagrammatic section through the tube of a microscope whose general outward appearance is shown in Fig. 13. The compound objective lens, *Ob*, is placed so as to furnish a diverging beam of light from an object, *PQ*, which is focused in an inverted, real image at *P'Q'* after passing through a lens, *C*. The lens *O* is so placed as to furnish to the eye, *E*, an enlarged virtual image of *P'Q'* at *P''Q''*. Variations in the magnifying power are obtained by employing objective lenses with different focal lengths, and also by using different combinations of the ocular lenses *O* and *C*. Owing to the need of frequent changes of objective lenses in the microscopical study of rock sections, it is convenient to attach these lenses to the lower end of the tube by means of a spring clamp, *k*, in Fig. 13, obviating the screwing and unscrewing of the lenses.

For most purposes the light used is transmitted by reflection from a mirror beneath the stage passing through a lens *S* (Fig. 12), which condenses it somewhat on the object placed upon the stage. When it is desired to increase the condensation or illumination, a lens of shorter focus is inserted above *S*, by shifting a handle *b* (Fig. 13), which moves the upper lens to the center of the stage. A proper adjustment of the illumination is obtained by means of a screw beneath the stage which raises or lowers the tube in which the lower lens *S* is fixed. In order to cut off marginal rays and reduce the illumination to a narrower beam through the center of the lens an iris diaphragm is placed beneath the lens *S* at *i* (Fig. 12). It is regulated by a knob at *Z* with an indicator registering the diameter of the opening on a scale indicating millimeters.

In order to determine the magnifying power of a combination of lenses a scale or micrometer etched on glass is placed so as to coincide with the real image at *P'Q'*. The virtual image of this scale is compared with a scale of hundredths of millimeters placed on the

stage of the microscope, and the ratio between the two is noted. The value of a unit distance on the micrometer scale, in parts of a millimeter, is in this way fixed for a given combination of lenses.

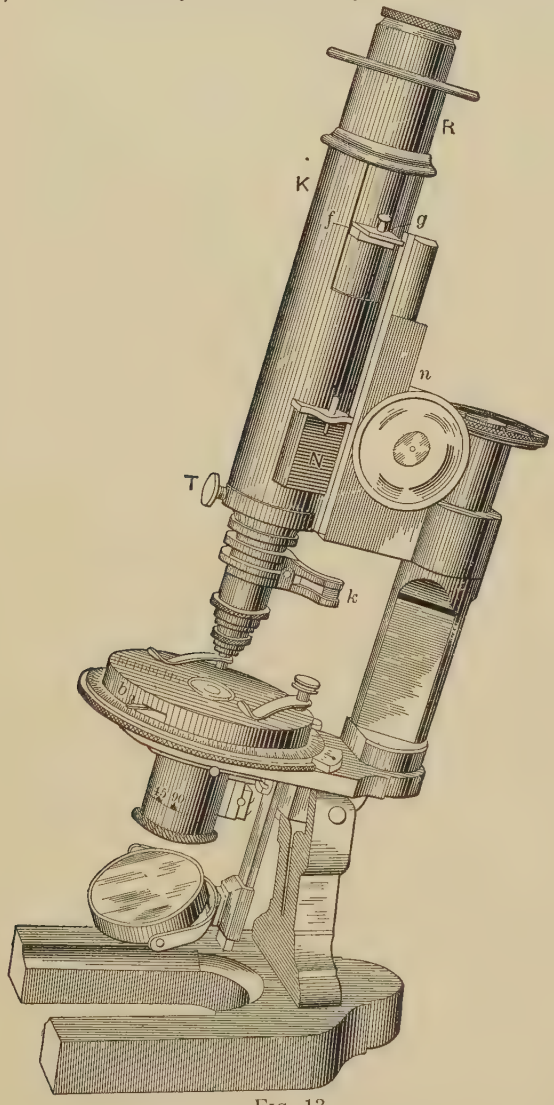

FIG. 13.

Another method consists in using a shifting eyepiece furnished with cross hairs to mark a point on the object to be measured and a graduated screw thread to measure the distance through which the cross hairs are moved over the object.

To measure an angle between two lines in the plane of the stage of the microscope, that is, in the plane of a rock section resting upon it, it is necessary to rotate the stage about the axis or the line of sight of the microscope; or the ocular containing cross hairs may be rotated. The ordinary method is to rotate the stage, which is provided with a graduated circumference and a vernier scale. The cross hairs serving at datum lines, intersecting one another at 90°, are placed in the focus of the real image at $P'Q'$. To accommodate different eyesights the lens O is adjustable by means of a sliding tube, so that it may be focused on the fixed cross hairs. In order that the stage may rotate about the center or line of sight of the microscope, the tube carrying the objective lens is centered to the stage by means of two screws, one of which is shown at T (Fig.14). The method of adjustment is understood from the figure. Let p be a point in an object on the stage which has been placed beneath

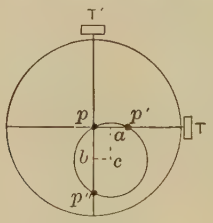

Fig. 14.

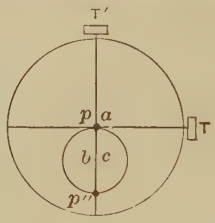

Fig. 15.

the intersection of the cross hairs, and let the circle p, p', p'' be the path described by the point when the stage and object is rotated 360°. Clearly the center of the stage is at C. To bring the center of the lens system and cross hairs in line with c it is necessary to turn the screw T so as to move the cross hairs so that their intersection is half way between p and p' as at a, and to turn the screw T' so that the intersection of the cross hairs is half way between p and p'', as at b. This is accomplished by rotating the stage until the point p reaches p' on the line of one of the cross hairs, and adjusting with the screw T until the point p moves as far as a. Then the rock section or other object is moved on the stage until the point p is beneath the intersection of the cross hairs (Fig. 15). The stage is then rotated until the point is at p'' and the adjustment is made by the screw T' until the point reaches b. The center of the circle, c, will have moved to the intersection of the cross hairs. Owing to the wear of the socket of the objective lenses in the clamp k it is not possible to maintain a perfect centering for any one lens. Its center shifts each time it is moved. For this reason other methods of rotation

have been adopted in other forms of microscope. In one the stage and objective lens retain a fixed relation to one another and are rotated together, the ocular lenses and cross hairs remaining stationary. In another arrangement the ocular lenses and cross hairs rotate and the stage and objective lens remain stationary. Various forms of microscopes are described and figured in the work by Rosenbusch and Wülfing already cited.[1]

Luster of Minerals.—Reflection of light from the surface of minerals, their *luster*, considered independently of the kind of light, the color, varies with the character of the surface in the first instance; a smooth, continuous surface reflecting better than a rough one. From surfaces with similar smoothness the amount of light reflected varies with the index of refraction of the reflecting substance. Substances with higher refraction exhibit more brilliant lusters.

The names employed to describe the luster are of a very general character, such as *adamantine*, resembling the luster of a diamond; *vitreous*, resembling that of glass; *resinous*, like that of resin; *pearly*, like that exhibited by pearl, etc. As already said, one substance may exhibit different degrees of luster according to the character of the reflecting surface. The following examples of the highest luster of certain minerals show the correspondence between the luster and the average refraction and also the vagueness of the terms "adamantine" and "vitreous."

Aver. Refr.	Highest Luster.	
3.016	Adamantine	Pyrargyrite
2.969	"	Cinnabar
2.7115	"	Rutile
2.4278	"	Diamond
2.4007	"	Sphalerite
2.0288	"	Cassiterite
1.9519	"	Zircon
1.7659	Adamantine to vitreous	Corundum
1.6334	Vitreous	Tourmaline (colorless)
1.6011	"	Calcite.
1.5472	"	Quartz
1.5229	"	Orthoclase
1.4827	"	Sodalite
1.4336	"	Fluorite
1.3104	"	Ice

[1] The principal makers of petrographical microscopes are: In Germany, R. Fuess, Steglitz near Berlin; C. Leiss, Jena; E. Leitz; W. and H. Seibert; in Austria, C. Reichert, Vienna; in France, A. Nachet, Paris; in England, Swift & Son, London; in the United States, Bausch & Lomb, Rochester, N. Y.

Reflections from *inclusions* within transparent substances produce effects entirely foreign to the substances themselves. Such effects are frequently combined with interference phenomena, to be described later. As examples of the effect of simple reflection may be mentioned metallic reflection from inclusions within colorless minerals like quartz, feldspars, etc. The white color of many minerals is due to the reflection of light from minute inclusions, colorless themselves, having a lower index of refraction than the surrounding mineral; such as inclusions of gas and liquid in minerals, corresponding to the familiar case of gas in liquid, as in foam. It is not necessary that the inclosed substance possess a lower refraction than the surrounding one, for where both are colorless and the inclusions are abundant the effect is the same, since the light passes from the denser inclusion to the rarer substance containing it. A familiar example is that of water particles in air, and the appearance of white clouds.

When the size of the particles reflecting light is less than half a wave length of light ($\lambda_v = .000380$ mm.), the reflected light is blue like the sky. This phenomenon is exhibited by quartzes in certain rocks, and possibly sometimes by orthoclase (sanidine) and albite in others.

Phenomena produced by different degrees of refraction in adjacent substances are chiefly noticeable in thin sections of minerals and rocks mounted in Canada balsam, when seen in transmitted light under a microscope. These phenomena are useful in determining the character of minerals and other substances found in rocks and may be described as follows:

Outline and Relief of Mineral Substances in Thin Sections Mounted in Canada Balsam.—In the case of colorless material, as glass or crystal, it is evident that if the crystal and balsam have the same index of refraction and are equally colorless, the outline of one against the other will not be visible. There will be no refraction of the light in passing from one substance to the other. This case is nearly realized with quartz, orthoclase, or albite in balsam. It is more nearly realized when quartz crystals lie in perfect contact with one another, and is completely realized when several crystals of the same isotropic substance are in contact, such as small leucites. In the last case the outline between two individuals is not visible. In proportion as there is a difference between the refraction of a colorless crystal and that of the surrounding colorless matrix the outline of the crystal is more noticeable.

This is due to shadows of greater or less intensity occurring on edges which act as inclined surfaces producing reflections and refractions according to the angle of incidence. Light which strikes such an inclined surface outside the critical angle is totally reflected, and that passing through at other angles is diffused or condensed, as explained on page 116. The same phenomena occur along cracks in the crystal section. Outlines and cracks appear shadowed or illuminated with greater intensity as the difference between the refraction of the two substances in contact is greater.

Another phenomenon dependent on difference of refraction in the crystal and surrounding matrix, the balsam, arises from the unevenness of the artificial surface ground on the section of crystal. Light passing in parallel rays across this uneven surface is refracted in many different directions, because of the different angles of incidence at the irregular surface. Hence there are spots where refracted rays converge and others where they diverge, the former are more strongly illuminated, the latter less so. There results a mottled illumination of the surface of the crystal section, which is more pronounced the greater the difference in refraction of the crystal and balsam. The surface of the crystal is said to be *shagreened*.

The pronounced mottling and noticeable outline and cracks appear whenever there is considerable difference of refraction between the crystal and surrounding balsam, whichever is more highly refracting. These characters therefore distinguish minerals with relatively high index of refraction and also those with relatively low refraction. Among the rock-making minerals there are many with rather high refraction, such as pyroxene, olivine, and melilite, but there are very few with refraction noticeably lower than balsam, such as fluorite; with this may be compared water and gas as inclusions. Sections of minerals, like quartz, feldspar, and leucite, having nearly the same refraction as balsam, appear to have an extremely smooth surface, and to have scarcely visible cracks or outline. Consequently, when crystals of various kinds are in contact with one another in rock sections mounted in balsam, those whose refraction is noticeably different from balsam, higher or lower, appear in distinct relief as compared with minerals having nearly the same refraction as balsam. In like manner, the character of microscopic inclusions in minerals may be judged by means of the breadth of shadow along their margin. Gas bubbles in quartz have broader shadow margins than liquid inclusions of the same shape and size, and these have broader ones than glass inclusions whose refraction is nearly

the same as that of quartz. Of course the shape of the inclusion modifies the phenomenon.

Determination of the Relative Values of Indices of Refraction in Thin Sections of Minerals. Becke's Method.—An exceedingly simple and delicate method of determining the relative values of the refraction of two adjacent transparent substances in close contact has been described by F. Becke. It is based on the principle of total reflection of light passing from a denser to a rarer medium when the incidence is outside the critical angle. In Fig. 16 let D be a mineral plate having higher refraction than an adjacent mineral d, and let the plane of contact between them be vertical. A beam of transmitted light perpendicular to the section contains besides normal rays converging rays, which traverse the section in the manner shown in Fig. 16. That is, all rays passing across the contact plane from the rarer to the denser mineral pass through the plane, but those passing from the denser toward the rarer do not all pass through; those outside the critical angle are reflected back in the denser medium and increase the illumination on the side of the denser mineral. In cases where the critical angle is large, the two media having nearly the same refraction, the pencil of light which may be reflected to one side is extremely small, so that with a broad beam of light the whole illumination masks the phenomenon just described. By cutting down the beam by diaphragming, the effect of the reflected light is increased. It is also more noticeable the higher the power of the objectives.

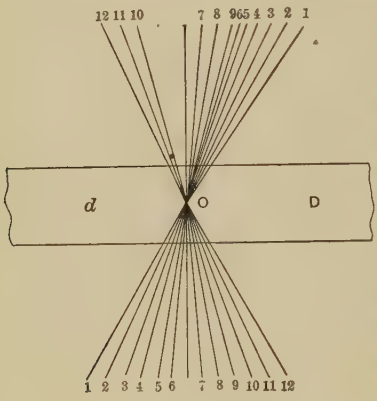

FIG. 16.

When the objective of the microscope is focussed on the middle of the contact plane, as at O in Fig. 17, the reflected rays B are evenly distributed about O' in the image $D'd'$. Upon slightly raising the tube of the microscope, as in Fig. 18, the reflected rays B appear to one side of O' and on the side of the mineral with higher refraction D'. Upon sinking the tube, as in Fig. 19, the reflected rays appear on the side of O' toward the mineral with lower refraction d'. When a microscopic crystal of apatite surrounded by quartz is observed in transmitted light, since it has a stronger refraction than

quartz, it will appear brightly illuminated when the tube of the microscope is raised above the focus of the outline of the apatite. On the other hand, an inclusion of gas will appear brightly illuminated at the center when the microscope tube is lowered from the focus. This method is so delicate that it serves to detect differences of refraction amounting to 0.001. It is particularly valuable in distinguishing colorless minerals with nearly the same refraction, such as quartz, feldspars, the feldspathic minerals, and rock glass. Its

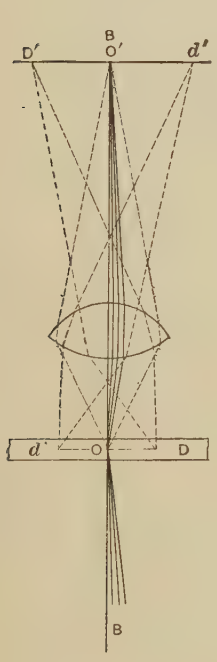

Fig. 17.

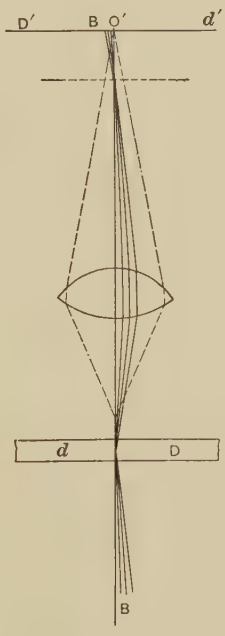

Fig. 18.

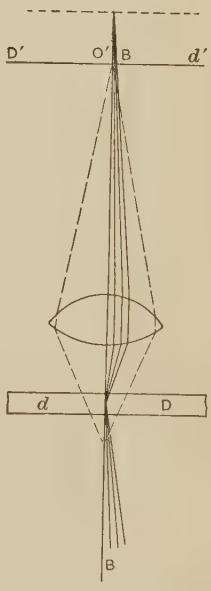

Fig. 19.

special application to these minerals will be described in connection with phenomena of double refraction.

Inclined Illumination.—When the light is shifted from the axis of the microscope, either by a lateral movement of the lower lens system, by the shifting of the mirror, or by shading one side of the beam of light by any means, the light and shade on either side of the boundary, between substances with different refractions, become still more pronounced, as Becke has pointed out. The phenomenon is understood from Fig. 20. When a beam of inclined rays passes

through a plate composed of several minerals having different indices of refraction, whose planes of contact are nearly normal to the section plane, the rays which pass from a mineral with lower refraction, d, to one with higher refraction, D, are spread apart; that is, the light coming from the edge of D nearest d is fainter than that coming

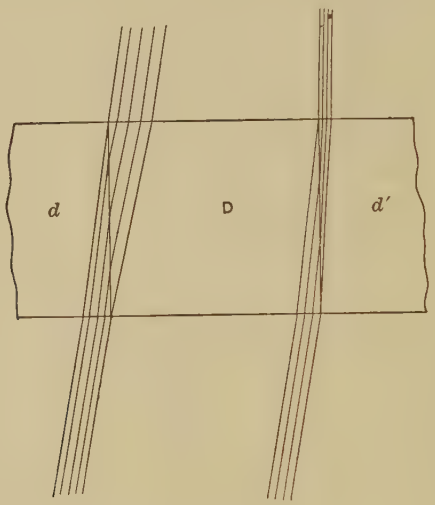

FIG. 20.

through the minerals on both sides of the edge. It appears in shadow. On the other hand, the rays which pass from the mineral, D, through d' with lower refraction than D, are condensed, so that this edge of the mineral D is brighter than the minerals on both sides of it. Thus, in general, for all bright edges or contact planes (Fig. 21, a), the min-

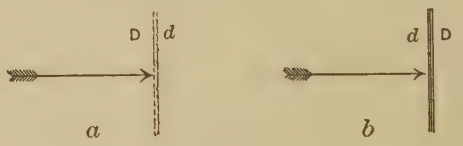

FIG. 21.

eral with higher refraction, D, is on the side from which the light comes, while for all dark edges or contact planes (Fig. 21, b), the mineral with lower refraction, d, is on the side from which the light comes.

This method of determining the relative indices of refraction of adjacent minerals is more sensitive than the Becke method already described, but care must be taken in noting the direction from which the inclined light enters the mineral section. It is to be remembered that the lens below the stage of the microscope reverses the path of inclined light coming from the mirror, and the objective lens reverses the image of the mineral section and the direction of the inclined light, so that the inclined light crosses the image of the section in the same direction as that in which it enters the lens beneath the mineral section. This will be evident from Fig. 12, p. 107.

Determination of the Index of Refraction.—The exact determination of the index of refraction is made on prisms cut from a crystal by observing the deflection of a ray of monochromatic light. It may also be determined from the angle of total reflection when the crystal is immersed in a denser liquid or is placed against a glass hemisphere—Kohlrausch's, Bertrand's, and Abbe's total reflectometers. Such methods are described in works on physics, and in Groth's Physikalische Krystallographie, and belong more to the realm of the mineralogist than to that of the petrographer. Less accurate methods, by means of which approximate determinations may be made of the principal indices of refraction or of the average refraction of doubly refracting crystals, are described in what follows:

Immersion in Liquids with Known Refraction. — By immersing fragments of transparent crystals in liquids whose refraction can be modified until it is the same as that of the crystal, and then determining the index of refraction of the liquid, it is possible to avoid the preparation of prisms from the crystal, which in some instances may not be suitable for cutting into prisms. But it must be noted, that, with doubly refracting crystal, only an average index of refraction can be determined by this means, unless definitely oriented fragments are compared with the liquid.

The method which has been employed in special cases by various physicists has been elaborated by Schroeder van der Kolk,[1] and made of general application. It consists in bringing the refraction of a liquid to agree as nearly as possible with that of a fragment of crystal immersed in it, and then determining the refraction of the liquid. The first is accomplished by observing the phenomena of dispersion or of concentration that takes place along the plane of contact between two media in the manner already described in the

[1] Kurze Anleitung zur mikrosk. Krystallbestimmung. Wiesbaden, 1898; and Tabellen zur mikrosk. Bestimmung, etc. Wiesbaden, 1900.

Becke method and with inclined illumination. Fragments placed in the liquid are observed in monochromatic light with a microscope, and the concentration of the liquid changed by admixture of another liquid until the crystal and liquid have the same refraction. It is evident that, on account of the sensitiveness of these methods of recognizing differences of refraction in adjacent media, it will not be possible to adjust the liquid to correspond at one time to all of the fragments of a crystal with noticeable double refraction. When the orientation of a fragment or of a section of a crystal is known, it is possible to adjust the refraction of the liquid to that of a ray of light vibrating in a particular direction in the crystal plate.

When there is a noticeable difference in the refraction of the liquid or crystal with respect to different colored light, that is, when the dispersion is strong, it may happen that, when the immersed crystal and liquid have like indices of refraction for light of medium wave length, yellow, the index of refraction for blue in the liquid is higher than that in the crystal, while the index for red in the liquid is lower than that in the crystal. This is on the assumption that the dispersion in the liquid is stronger than that in the crystal, which is the common case. When observed with inclined illumination, it will be found that one edge of the crystal fragment is illuminated by blue light while the other is red. The blue edge will appear on that side of the crystal which would be brightly illuminated when the crystal is immersed in a medium with higher refraction. That is to say, it would be the bright edge if monochromatic blue light were used, and it would be the shaded edge were red monochromatic light used. The red edge of the crystal is that in which the reverse phenomena would be observed in blue and red monochromatic light. The appearance of red and blue edges on the opposite sides of an immersed crystal fragment is an indication that the crystal and liquid have like indices of refraction for intermediate colors.

Various liquids may be employed, some of which are better adapted to the purpose than others. Certain oils have the advantage of maintaining their character and consistency, with slight change, for considerable lengths of time. Changes of temperature modify the refringence of liquids, as do also changes of concentration through evaporation of a part of the liquid. Such sources of error are to be guarded against during the operation. The following are some of the liquids recommended by Schroeder van der Kolk. The indices are for a temperature of about 15° C.

Water	1.333
Carbon tetrachloride	1.466
Beechnut oil	1.477
Xylene	1.495
Benzene	1.501
Cedar oil	1.516
Monochlorobenzene	1.527
Ethylene bromide	1.536
Clove oil	1.544
Nitrobenzene	1.554
Monobromobenzene	1.561
Bromoform	1.588
Cinnamon oil	1.605
Monoiodbenzene	1.621
α-Monochloronaphthalene	1.639
α-Monobromonaphthalene	1.658
Iodmethylene	1.740
Sulphur in iodmethylene	1.83

Viola's Method of determining the index of refraction of a mineral in thin section, when it is in contact with a substance whose refraction is known, is a quantitative application of the Becke method of noting the difference in refraction of two adjacent substances. It depends upon observing the diameter of the iris diaphragm when the Becke effect is obtained, but this is an ill-defined phenomenon, and permits of considerable divergence of judgment on the part of observers. According to Viola,[1] the difference between the indices of refraction of two adjacent substances, $n_2 - n_1$, is proportional to the square of the diameter, D, of the opening in the diaphragm for the illumination of the field which permits of the observation of the Becke effect, or, approximately, $n_2 - n_1 = \lambda D^2$, where λ is a constant to be determined for a particular combination of lenses. This method permits the determination of the index of refraction of one substance when the other factors in the equation are known. It is independent of the thickness of the mineral plate; and, if the phenomenon studied were sharply defined, the method would be extremely useful.

De Chaulnes's Method of determining the index of refraction of a medium depends upon the change of focus caused by placing a plate of the substance over an object in the focus of a lens. It will be understood from Fig. 22. The point, o, is in the focus of the

[1] Tschermaks Min. u. petrogr. Mitth., XVI, 1896, p. 150.

objective of a microscope; over it is placed a plate, M, of an isotropic medium, as glass; the focus of the point, o, now appears at p, because a ray, od, would be refracted to dg upon emerging from the plate. This necessitates raising the lens a distance, op, in order to bring the point in focus. The relation between the distance, op, the thickness of the plate, ob, and the index of refraction, may be gotten from the figure. Since $\tan i = \frac{db}{bp}$ and $\tan r = \frac{db}{bo}$, if $bo = T$, the

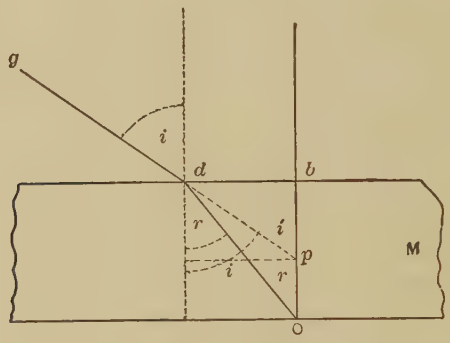

Fig. 22.

thickness of the plate, and $bp = T - h$ where $h = op$, the change of focus, then $\frac{\tan i}{\tan r} = \frac{T}{T-h}$. For small values of i and r the ratio between the tangents is nearly the same as between the sines, so that $n = \frac{\sin i}{\sin r} = \frac{\tan i}{\tan r} = \frac{T}{T-h}$. The value of h may be determined by the graduation of the micrometer screw on the microscope. The thickness of the plate may be measured directly with an ocular micrometer, or by means of the micrometer focussing screw, noting the change of focus from the point o to a point on the upper surface, b; or by measuring the distance from the bottom to the top of the plate through the plate by means of the micrometer focussing screw. This distance is $T_1 = T - h$. The displacement of focus, h, when the plate is superimposed on a point, o, is then noted:

$$n = \frac{T_1 + h}{T_1}.$$

It is found that where the thickness of the plate is very small, as in most rock sections, the errors in the ordinary methods of deter-

mining the thickness seriously affect the value of the index of refraction. This method is unsatisfactory for determining the refraction of minerals in rock sections.

Polarized Light.

In order to understand what is involved in the conceptions "polarized" light and "ordinary" light, it is necessary to review some further principles connected with simple harmonic motion.

Composition and Resolution of Simple Harmonic Motion.—If two simple harmonic motions affect one body at the same time, the resultant motion will be a regular periodic motion whose character depends on the directions in which the impulses are applied and the periods and phases of each vibratory motion. Let us consider several of the simpler cases: (1) If the two motions are equal in period, phase, and amplitude, and are in the same direction, the resultant will be a vibration of double the amplitude of one of the motions. (2) If the two motions are equal in period and amplitude, and are in the same line, but differ by half a phase, the resultant will be zero, rest. (3) If the two motions are equal in period and amplitude, but take place at right angles to one another (Fig. 23), and are in the same phase, the resultant is a vibration at 45° to each, and the amplitude is equal to the diagonal, *OP*, of the parallelogram made from the amplitudes of the two component motions, *OA* and *OD*. For, when the particle at *O* tends to move toward *A* and toward *D* at the same rate, the resultant motion will be found by constructing the parallelogram of motion on *OA* and *OD*, the resultant being the diagonal *OP*. (4) If the second motion is half a period behind the first, when the first starts to move from *O* toward *A*(+), the second is starting from *O* toward *C*(−) at the same rate. The resultant will be *OQ*. Each of these compositions results in simple harmonic motion—vibration—in a straight line. (5) If the second motion is one quarter of a phase behind the first, so that when the first motion is beginning its positive, vertical movement at *O*, the second motion is just leaving its negative point of maximum elongation at *C*(−), the resultant is a circular motion from *C* to *A* in the circle *CADB*. (6) Similarly, if the second motion were three quarters of a phase behind the first, or one quarter ahead,

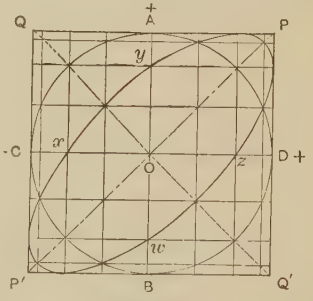

FIG. 23.

the resultant motion would be in a circle from D to A, opposite to the fifth case.

In like manner it can be shown that if the phasal difference is other than one, two, or three quarters of a period, the resultant motion will be an ellipse, as in the curve *xyzw*, in which case the difference of phase is seven eighths of a period.

If the two motions have the same period, but different amplitudes, and act at right angles to one another, the resultant motions are in straight lines when the phases are the same, or when one is half a period from the other. In all other cases the resultant motion will be in an ellipse.

By a reverse process of reasoning, any of the regular periodic motions just mentioned may be resolved into two component simple harmonic motions acting at right angles to one another. Thus a simple vibration in any given direction, *OP* (Fig. 24), may be resolved into two vibrations acting in directions *OA* and *OD* at right angles to one another, which will be in the same phase, but whose amplitudes will depend on the angular position of *OP* to *OA*, *OD*. When *DOP* is 45° (Fig. 24, *a*), the amplitudes will be equal, otherwise not (Fig. 24, *b*).

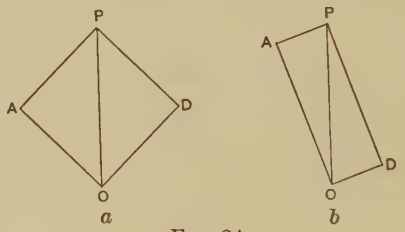

FIG. 24.

These simpler cases are used in explaining the behavior of monochromatic light, and are reviewed more particularly for this reason.

It is important, however, to recollect that, when simple harmonic motions of different periods, corresponding to vibrations of light of different colors, are compounded, there results a periodic curved motion of greater complexity. These highly complex periodic motions may in like manner be resolved into two harmonic motions acting at right angles to one another.

Composition of Wave Motion.—Two wave motions acting along the same line and in the same plane combine to form a wave motion whose character depends upon the wave lengths (periods of vibration) and the phases of the two motions. The resultant may be derived from a diagram of wave forms, or harmonic curves.

If the two waves have the same wave lengths and the same phases, but different amplitudes, the case is expressed in Fig. 25 when

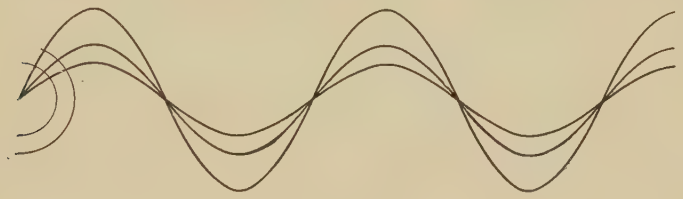

FIG. 25.

the resultant curve has the same wave length and phase, but an amplitude equal to the sum of the amplitudes of the component waves.

If the two waves have the same wave lengths, but their phases differ by half a wave length, and the amplitudes are different, the resultant curve has the same wave length, but the amplitude is equal to the difference between the amplitudes of the two waves (Fig. 26).

FIG. 26.

In general, the wave form resulting from the composition of two or more harmonic curves in one plane may be found by plotting each with its proper wave length, amplitude, and phase, and constructing the resultant curve from the algebraic sum of the ordinates of the wave forms at successive points along the direction of transmission. The form of the resultant wave form becomes more intricate, the greater the number of components with different wave lengths. Hence the wave form of white light is extremely complex in form, because of the number of wave motions of different periods of vibration that combine to make it. Furthermore, the light that reaches us from the sun, being set in motion by innumerable vibrations in all directions, is a composite harmonic motion of the utmost complexity, whether considered from the point of view of the transverse periodic vibration or of that of the harmonic curve along the line of transmission. This extremely complex motion is that of so-called *ordinary* or *common* light, or that coming to us from the sun.

But, as already said, any harmonic motion, however complex, may be resolved into two or more component harmonic motions acting in straight lines, making any angle with one another. Consequently, the complex vibrations of *ordinary* light may be resolved into simpler vibrations acting in two planes at right angles to one another, or at any other angle. Light whose vibration takes place in a straight line, and whose wave is therefore transmitted in a plane, is called *plane polarized* light. Its character is much more easily comprehended than that of *ordinary* light. Light whose vibrations take place in a circle or ellipse is called *circularly polarized* or *elliptically polarized* light.

As just stated, periodic vibratory motion, however complex, can be resolved into simple harmonic motion acting in two directions at any angle with one another. So the complex vibrations of *ordinary* light can be reduced to the simple vibrations of plane polarized light. This may be brought about in various ways.

Polarization by Reflection and Refraction.—When ordinary light strikes a plane surface with inclined incidence, the vibrations, which in an isotropic medium were taking place freely in all directions perpendicular to the direction of transmission, upon reaching the inclined surface of a denser medium appear to have their freedom restricted in all directions except in that parallel to the surface. The degree of restriction varies from zero in this direction to a maximum at right angles to it. The rate of variation and the extent of it also appears to vary with the angle of incidence. It should disappear entirely when the incident angle is zero, that is, when the light travels perpendicular to the surface between the two media.

The result of this probable difference of resistance is that the vibrations are resolved more and more completely into vibrations in two lines, one parallel to the surface, the other at right angles to the first. Consequently, the light that is reflected, and also that refracted, is more or less completely polarized, according to the angle of incidence. Complete polarization takes place when the reflected ray and refracted ray are at right angles to one another. The angle of incidence, therefore, at which complete polarization takes place, depends upon the relative optical density of the two media. Following Fresnel's theory, the polarized reflected light vibrates perpendicular to the plane of incidence and parallel to the surface of reflection. The polarized refracted ray in isotropic media vibrates in the plane of refraction, that is, at right angles to the direction of vibration of the reflected ray.

Polarization by Anisotropic Media.—It has been learned by observation that in isotropic media light may be transmitted in all directions with the complex vibrations of ordinary light, or with various forms of simpler vibrations, such as produce plane polarized, circular, or elliptical polarized light. But in anisotropic media the mode of vibration of transmitted light is rigidly conditioned by the character of the medium. In most cases the vibration is that of simple harmonic motion in a line perpendicular to the direction of transmission producing plane polarized light; the position of the plane of vibration having a definite relation to the molecular structure of the medium. In some cases the imposed vibration is circular in certain directions, in others elliptical, in others in straight lines. The velocity of transmission is also definitely related to the direction, that is, to the molecular structure. These relationships being highly characteristic of various classes of crystals, and even of specific mineral compounds, become of the first importance in their identification. The phenomena exhibited by calcite illustrate the behavior of light in passing through anisotropic media and will serve as an introduction to the general discussion of the subject.

Double Refraction in Calcite.—If a crystal or cleavage piece of calcite in the form of a rhombohedron be placed in the path of a small beam of ordinary light coming from an opening in a screen, and held so that the light enters the crystal perpendicular to one face (Fig. 27), two images of the signal will appear at the other face of the crystal which is parallel to the first, the two having the same illumination (Fig. 28). If the crystal is rotated about a line normal

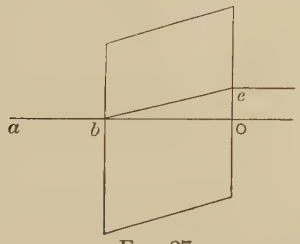

Fig. 27.

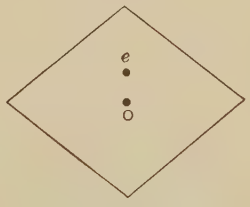

Fig. 28.

to the face through which the light passes, one image remains stationary, while the other moves in a circle around it (Figs. 29 and 30). Evidently the stationary image is directly in the axis of rotation, and the light has come through the crystal without deviation from a straight line, which would happen if the calcite were isotropic and the incident light at right angles to the surface. The second image

is illuminated by light that has been refracted, although the angle of incidence is zero. It behaves in an extraordinary manner, as compared with light passing through an isotropic medium. It is called the *extraordinary ray.* The other, which in fact behaves as though it were passing through an isotropic medium, is called the *ordinary ray.* When the crystal is turned so that its face is inclined

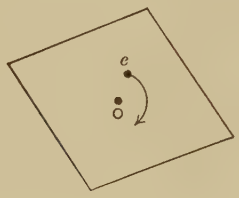

Fig. 29.

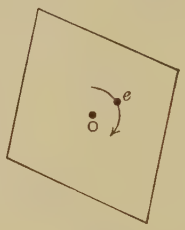

Fig. 30.

to the incident light both the ordinary and extraordinary rays are refracted. The crystal is said to be *double refracting* or *birefringent.* This is the case with all anisotropic media.

If a second calcite crystal like the first, having parallel faces and like thickness, is placed in front of the first, so that it is in the same crystallographic orientation (Fig. 31), with faces parallel each

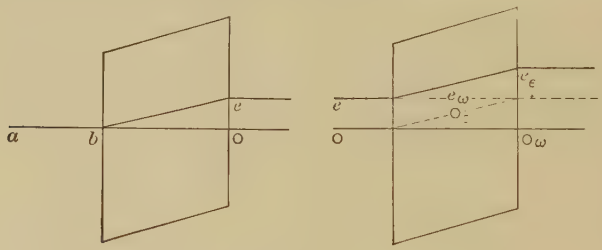

Fig. 31.

to each, and the longer diameter of the rhombic face horizontal, the two images seen in the first crystal appear on the front face of the second crystal but farther apart (Fig. 32); twice as far if the two crystals are equally thick. The effect is as though the thickness of the first crystal had been doubled. If, however, the first crystal remains stationary and the second crystal is rotated about a line normal to the face through which the light passes, the direction of incidence, instead of two images there are four (Fig. 33), differently illuminated according to the degree of rotation, two alike and fainter than the other two which are also alike, but not so bright as the two

images seen in the first calcite crystal. Just after the beginning of rotation the appearance of the spots is that shown in Fig. 33. The two brighter ones occupy nearly the same positions as the two before rotation began. The two faint ones are half way between and near together. As rotation of the second calcite proceeds it

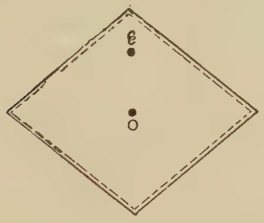

Fig. 32.

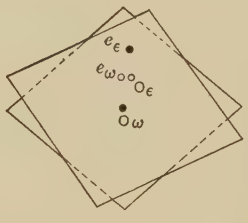

Fig. 33.

is seen that one of the bright spots remains stationary, o_ω, while one of the faint spots, o_ϵ, moves in a circle around it. In like manner the other faint spot, e_ω, remains stationary and the other bright spot, e_ϵ, moves in a circle around it, the motion being in the same direction in both cases. The illumination of the spots changes with the degree of rotation, the brighter ones fading as the fainter ones brighten, until 45° of rotation has been reached when all four spots are equally illuminated (Fig. 34). Passing beyond this the same change continues until at 90° of rotation (Fig. 35), the first two

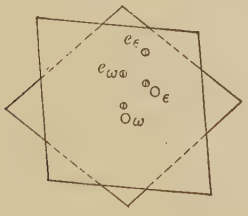

Fig. 34.

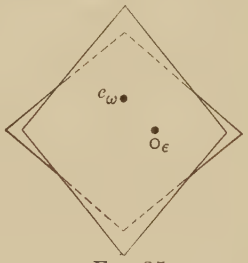

Fig. 35.

bright spots, o_ω, e_ϵ, have faded completely out and the two faint spots, o_ϵ, e_ω, have become bright and alone are visible. Continuing the rotation beyond 90° four spots again appear: two bright and two faint. At 135° of rotation the four are equally illuminated. Beyond this they continue changing in illumination until at 180° of rotation (Fig. 36) two have disappeared, but the two bright ones have come together and form one spot doubly illuminated (Fig. 37).

If the rotation is continued through 360° the phenomena repeat themselves in the reverse order to that just described.

To understand the changes of position of the two pairs of spots it is only necessary to note that from the first calcite crystal there proceed two beams of light, each of which upon entering the second crystal is separated into two, one passing through as an ordinary the other as an extraordinary beam (Fig. 27). Upon rotation the ordinary component remains stationary, the extraordinary revolves around it.

From the variations in illumination of the spots it is evident that the amplitude of vibration of the light in the several beams changes from zero to a maximum, according to the relative positions of the two calcite crystals. This could not happen if the light

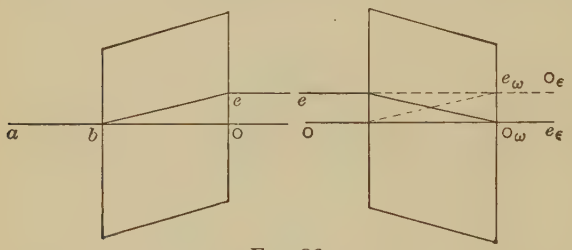

Fig. 36.

Fig. 37.

coming from the first calcite vibrated as *ordinary* light, like that entering it from the screen, for the illumination of the two spots seen in the first crystal does not change upon rotation of the crystal. Therefore, the light emerging from the first calcite must be polarized, and the variations in the illumination of the four spots seen in the second calcite correspond to changes which would take place in the amplitude of vibration of the several beams, if each beam were composed of light vibrating in a single plane, that is, if it were plane polarized light; and since the two pairs of spots, or two pairs of beams, an ordinary and extraordinary in each pair, behave in an opposite manner with respect to their illumination, the ordinary component of one pair starting bright and fading, while the ordinary component of the other pair begins faint and grows bright, it is evident that the planes of vibration of the two polarized beams from the first crystal are not in parallel positions but in contrary positions, that is, at right angles to each other. This is true for all kinds of anisotropic crystals, namely, that, with the exception of a limited number of possibilities to be described later, for every pair of extraor-

dinary and ordinary rays there are two planes at right angles to one another, in one of which the extraordinary ray vibrates, the ordinary ray vibrating in the other plane. The position of these planes depends on the molecular structure of the crystal, and for a given direction of transmission of light has a definite orientation in the crystal.

For calcite crystals it has been found that one plane of every possible pair passes through the principal crystallographic axis, *c*, of the crystal. In the calcite rhombohedron already described one plane of vibration passes through the shorter diagonal of the rhombic face, the other plane passing through the longer diagonal at right angles to the shorter one. The phenomena of varying intensities of light of the extraordinary and ordinary beams seen upon rotation of one calcite in front of another can be explained equally well in whichever plane the vibration of the extraordinary ray is considered to take place. It is customary to assume that the extraordinary ray vibrates in the plane passing through the shorter diagonal of the rhombic face and the ray of light, that is, in the plane passing through the principal axis of the crystal; the vibrations of the ordinary ray taking place at right angles to the principal axis and to the ray of light.

The phenomena of the four spots just described may then be explained in the following manner: In Fig. 38 let *O* be the image made by the plane polarized light of the ordinary beam whose vibra-

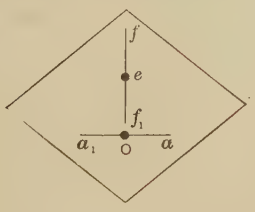

FIG. 38.

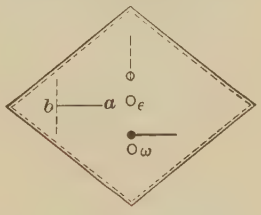

FIG. 39.

tions take place parallel to aa_1, oa being the amplitude of the vibration. Let *e* be the image made by the extraordinary beam whose vibrations take place parallel to ff_1, ef being the amplitude of the vibration, $oa = ef$.

Consider first what happens to the beam, *O*, upon entering the second calcite. It should be resolved into two components vibrating in planes at right angles to one another; an ordinary component vibrating parallel to the direction of the longer diagonal of the second calcite rhomb, and an extraordinary component vibrating in a plane

at right angles to the longer diagonal. (1) When the two calcites are parallel to one another (Fig. 39), the beam entering normal to the face is vibrating in the direction *ab*, which is parallel to the longer diagonal of the second calcite. Therefore, it can continue to vibrate without change of direction, the whole of it passing through the second calcite as an ordinary ray without refraction and with the same amplitude, since the calcite is almost perfectly transparent and colorless. The beam will appear at O_ω (Fig. 39). The component which should pass through as an extraordinary ray and appear at O_ϵ has no amplitude of vibration and is not visible.

(2) When the second calcite is rotated a small angle from its first position (Fig. 40). The image, O_ω, of the ordinary component remains stationary, that of the extraordinary component, O_ϵ, rotates about it. The amplitude of each is found by means of the parallelogram of motion, in which *ba* represents the amplitude and direction of the vibration of the beam, *O*, coming from the first calcite, and *bc* and *bd*, parallel to the diagonals of the second calcite, correspond to the directions of vibration of the two resultant rays; constructing a parallelogram on *ba* as a diagonal, *bc* represents the amplitude of vibration of the ordinary component, O_ω, and *bd* the amplitude of the extraordinary component, O_ϵ.

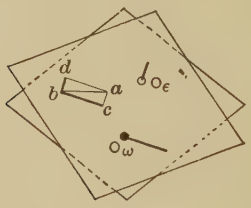

FIG. 40.

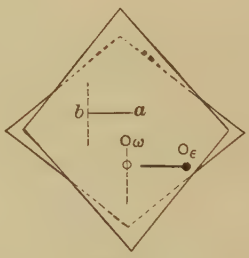

FIG. 41.

It is easily seen that as the second calcite is rotated further, the direction *ba* depending on the first calcite and remaining fixed, the value of *bc* decreases while that of *bd* increases. They become equal when the second calcite reaches the 45° position. Turning beyond this they continue to change until the second calcite reaches the 90° position (Fig. 41), when all of the light from the first calcite passes through the second vibrating parallel to the shorter diagonal, as an extraordinary ray, O_ϵ, with amplitude equal to *ba*. The image at O_ω is not visible, the amplitude of the component being zero.

The discussion being carried on in the same manner for the re-

mainder of a complete rotation of the second calcite, and for the two components of the beam, *e*, will explain the whole phenomena as first described.

Optically Uniaxial Crystals.—Investigation of calcite shows that for all directions of transmission one ray travels with constant velocity as though the medium were isotropic, while the other ray travels with different velocities in different directions, the variations, however, are regular and in such order that there is a single direction in the crystal in which the extraordinary ray travels with a minimum velocity, as is the case with calcite, or a single one in which its velocity is a maximum, as in quartz. From this direction, when a minimum, the velocity of transmission increases with a change of direction until it is a maximum in a direction at right angles to that first named, the rate of change in velocity being proportional to the radii vectores of an ellipse whose minor and major diameters are twice the minimum and maximum velocities. In the second case the variation is of the same kind, but in the opposite direction, that is, from the single direction of maximum velocity it diminishes proportionally to radii vectores of an ellipse until it reaches a minimum at right angles to the first named direction.

This change of velocities obtains in all planes passing through the single direction of minimum velocity in one case, and of maximum velocity in the other. The wave front which would be produced by light radiating from a point within such a medium and traveling as extraordinary rays would be an ellipsoid of rotation, the axis of rotation being the single direction in which the velocity is a minimum in one case, or a maximum in the other. The wave front of the ordinary rays radiating from the same point would be a sphere.

It has also been determined that the ordinary and extraordinary rays have the same velocity of transmission when they travel in the single direction of minimum or maximum. In this direction the diameter of the sphere is equal to the axis of the ellipsoid of rotation. That is, the sphere and ellipsoid are tangent to one another at the extremities of this axis (Fig. 42). In the first case (*a*) the sphere is within the ellipsoid, in the second case (*b*) the sphere is outside the ellipsoid. Crystals of the first kind (*a*), like calcite, are called *optically negative;* those of the second kind (*b*), like quartz, are called *optically positive.*

The direction in which the ordinary and extraordinary rays travel with equal velocities is called the *optic axis.* And, since there

is only one direction of this kind in such crystals, they are called optically *uniaxial*. Attention is called to the fact that the optic axis is a *direction*, not a fixed line, in a crystal. It may be imagined to pass through any point on which attention is for any reason fixed. It is to be noted that in uniaxial crystals all extraordinary rays vibrate in planes passing through the ray and the direction of the optic axis, sometimes called principal optic sections. Further, all ordinary

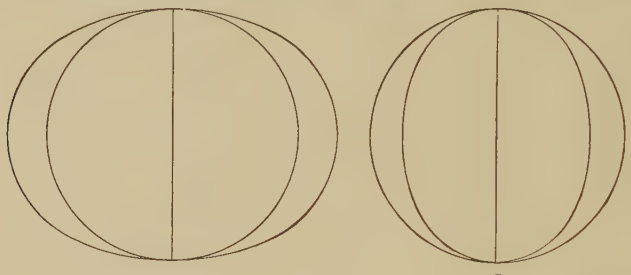

FIG. 42.

rays vibrate at right angles to the plane passing through the ray and the optic axis, that is, they vibrate at right angles to the optic axis.

From what has been said, it is clear that the index of refraction of the ordinary ray, n_o or ω, is constant for all directions of transmission. The index of refraction of the extraordinary ray varies with the direction of transmission; but since this variation is definitely related to an ellipse, one of whose diameters is proportional to the index of refraction of the ordinary rays, it is only necessary to know the index of refraction corresponding to the ray traveling along the other diameter of the ellipse, that is, at right angles to the optic axes. This is designated by n_e or ε.

In optically negative crystals $\omega > \varepsilon$, since the velocity of the extraordinary rays is greater than that of the ordinary, that is, $V_e > V_o$, and $\omega = \frac{1}{V_o}$, $\varepsilon = \frac{1}{V_e}$. In optically positive crystals $\omega < \varepsilon$, since $V_o > V_e$. The amount of difference between the two principal indices of refraction is a measure of the strength of double refraction, which is further discussed on p. 144.

Refraction of Light in Uniaxial Crystals.—It is important to note the behavior of light transmitted through a uniaxial crystal in various directions. It may be illustrated for the case of calcite. In Fig. 43 let mm, be a plane cut on calcite parallel to the optic axis, and let P, P_1, P_2, be rays of a parallel beam of monochromatic light

meeting it at an inclination, the plane of incidence being parallel to the optic axis. Employing Huyghen's construction to find the direction of the ordinary and extraordinary component of each ray, there is constructed at a the wave surfaces: first, a section of a sphere whose radius is to the distance bc as the velocity of the ordinary ray, V_o, in calcite is to the velocity of the light in air, V, that is, the radius $=\frac{bc}{n^o}$; second, a section of an ellipsoid of rotation whose longer diameter is at right angles to the optic axis, and whose length is to the diameter of the sphere as $V_e : V_o$ or as $\frac{1}{n_e} : \frac{1}{n^o}$. The tangents from c to each of these wave surfaces give the wave fronts, and the points of tangency, the directions of the ordinary (o) and extraordinary (e) rays. In this position the extraordinary ray is refracted more than the ordinary.

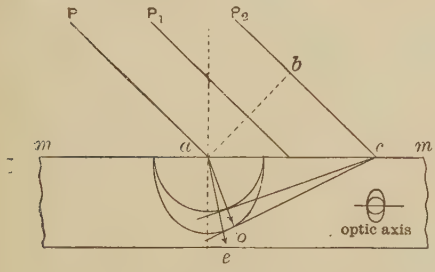

FIG. 43.

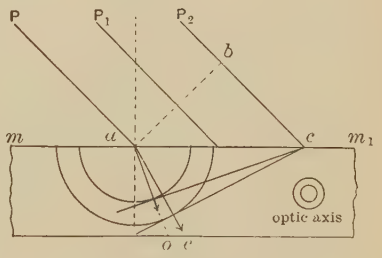

FIG. 44.

When the plane of incidence is perpendicular to the optic axis, the refraction is like that shown in Fig. 44. The direction of the optic axis is normal to the plane of drawing, therefore, the sections of wave surfaces for the ordinary and extraordinary components are circles in each case, whose diameters correspond to V_o or $\left(\frac{1}{n_o}\right)$ and V_e or $\left(\frac{1}{n_e}\right)$ respectively. The tangent planes from c show the directions of the ordinary (o) and extraordinary (e) rays, and in this position the extraordinary ray is refracted less than the ordinary.

It follows from these opposite conditions that there must be some position of the plane of incidence for this section plate of calcite, in which the extraordinary ray is neither more nor less refracted than the ordinary ray. In this case the angle of refraction is alike for the ordinary and extraordinary ray; that is, $\sin r_e = \sin r_o = \frac{\sin i}{n_o}$, in which n_o is the index of refraction for the ordinary ray. When the incidence is normal to the surface of a plate cut parallel to the

optic axis, the conditions of transmission of the ordinary and extraordinary components are shown in Fig. 45. The surface mm_1 is parallel to the optic axis, and the plane of the diagram is also parallel to the optic axis. When the rays PP_1P_2 reach the surface mm_1 at the same moment, the ordinary components of each proceed with the same velocity, $V_o - \left(\frac{1}{n_o}\right) -$, and their wave front at a given moment is tangent to the circular sections of the spheres. At the same moment the wave front of the extraordinary components is tangent to the elliptical sections of the ellipsoids constructed about each sphere. In this position the tangent to the ellipse is at right angles to the major axis of the ellipse, and the extraordinary ray has the same direction as the ordinary. It is advancing faster than the ordinary. In this position the extraordinary ray is not refracted.

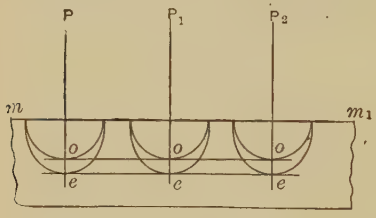

FIG. 45.

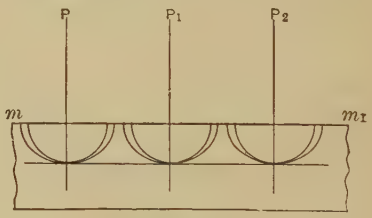

FIG. 46.

In like manner, when calcite is cut perpendicular to the optic axis and light strikes the surface at normal incidence (Fig. 46), both components are transmitted without refraction and with the same velocity, which is easily understood from the diagram.

When the mineral plate is cut at an inclination to the optic axis and the incident light is normal to the surface of the section, the

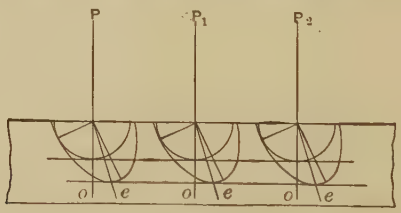

FIG. 47.

extraordinary ray is refracted while the ordinary ray is not, as will be understood from Fig. 47.

In each of the cases just given the plane of incidence for each ray passes through the ellipsoid or wave surface in such a manner as to divide it symmetrically, either passing through the optic axis, axis of rotation, or perpendicular to it. The points of tangency of

the plane wave front with the ellipsoids for each extraordinary ray will therefore be in the plane of incidence for that ray, that is, in each case the extraordinary ray is refracted in the plane of incidence, as is the ordinary; but, in case the plane of incidence is inclined to the optic axis of the crystal, it will not cut the ellipsoid for the extraordinary ray symmetrically, consequently the point of tangency of the plane wave front, with the ellipsoid for a particular ray, will not lie in the plane of incidence, and the extraordinary ray will not lie in the plane of incidence with the ordinary ray.

Nicol Prism.—On account of the strong double refaction of calcite and its colorless transparency, it has been employed as an apparatus for furnishing plane polarized light by preparing prisms of it in such a manner as to cut out one of the component beams, allowing one to pass through. Either the ordinary or extraordinary component may be cut out, according to the manner of cutting the prism. One form is a prism whose sides are parallel to rhombic cleavage planes, and whose end plane is nearly parallel to the third cleavage plane, the cross-section being rhombic. Such a prism is cut diagonally by a plane at right angles to the shorter diameter of the rhombic section, as shown in Fig. 48. The two parts are cemented together by Canada balsam which forms a transparent isotropie layer with an index of refraction 1.539. This is lower than the index of refraction of the ordinary ray in calcite, $\omega = 1.5583$, and higher than that of the extraordinary ray, $\varepsilon = 1.4864$. The ordinary component in passing from calcite into Canada balsam passes from a denser to a rarer medium. It is possible to place the film of balsam at such an angle that the ordinary component is totally reflected to the side of the prism and absorbed. The light which passes through is the extraordinary component and vibrates in the direction of the shorter diagonal of the rhombic section of the prism, and in a plane perpendicular to the film of balsam. This form of prism was devised by Nicol and is called a Nicol prism, or a nicol. In some cases the prism is cut with rectangular form, the sides being parallel to the diameters of the rhombic cross-section of the cleavage prism.

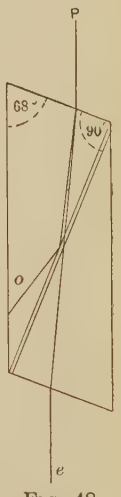

FIG. 48.

Another form has been devised in which the extraordinary component is cut out and the ordinary one passes through. This may be made shorter than that first described and in principle is as follows: The cleavage prism in the same crystallographic position as

the first is terminated by faces at right angles to the sides of the prism. The ordinary component for normal incidence travels parallel to the sides of the prism, while the extraordinary component is refracted at an inclination in the plane of the shorter diagonal of the rhombic section of the prism. It is possible to place the balsam layer, whose plane is normal to the plane of the shorter diagonal, at such an inclination to the extraordinary rays that these, in passing from the balsam into the calcite below, that is, from a denser to a rarer medium, will be totally reflected and absorbed in the sides of the prism. In such nicols the light passing through vibrates as ordinary rays parallel to the longer diameter of the rhombic section and parallel to the plane of balsam.

It is to be noted that both of these forms of Nicol prisms are frequently used on one petrographical microscope, the first form below the stage as a polarizer, the second form above as an analyzer. It is necessary, therefore, to make sure of the particular form of construction in determining the plane of vibration of the polarized light transmitted in each prism. In one it will be perpendicular to the film of balsam, in the other parallel to the film.[1]

Polarizer and Analyzer.—A Nicol prism used to supply plane polarized light to any apparatus is called a *polarizer*, and the direction in which the light vibrates upon leaving it is usually indicated in some manner upon it. A second Nicol prism used to investigate the character of the light after it has passed through some object under investigation is called the *analyzer*.

If there were isotropic media only between the polarizer and analyzer, the amount of light that would pass through the analyzer would depend upon the relative position of the two nicols. In Fig. 49 let PP' be the direction of vibration of light coming from the polarizer, and cP be the amplitude. If AA' is the direction of vibration of the light which passes through the analyzer, then the amount of light coming from the polarizer which can pass through is found by resolving the light in cP into the two components ca and cb parallel to the two directions of vibration in the calcite of the analyzer, AA' and BB'. Of these cb is reflected from the balsam film and absorbed, while ca passes through.

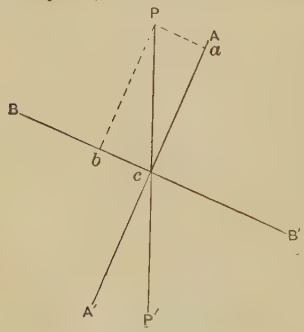

FIG. 49.

[1] For details of construction of Nicol prisms see Rosenbusch and Wülfing's work, Part I, p. 148 et seq.

If the analyzer is rotated, the value of the component *ca* increases as AA' approaches PP' and is equal to cP when AA' is parallel to PP'. In this case the nicols are said to be parallel. The value of *ca* decreases as the angle between AA' and PP' increases until it becomes zero when the angle is 90°. In this position the nicols are said to be *crossed* and all light from the polarizer is cut off.

Behavior of Plates of Uniaxial Crystals in Polarized Monochromatic Light.—When thin plates of crystals with parallel plane surfaces are studied in polarized light the resulting interference phenomena are characteristic of the substance to such an extent that they become a means of identification. It is necessary, therefore, to consider the phenomena in detail.

In Fig. 50 ss' represents a section cut from a uniaxial crystal at an inclination to the optic axis. Let this plate be placed in a beam of plane polarized monochromatic light so as to be perpendicular to the rays rr'. At the point of entrance of a polarized ray

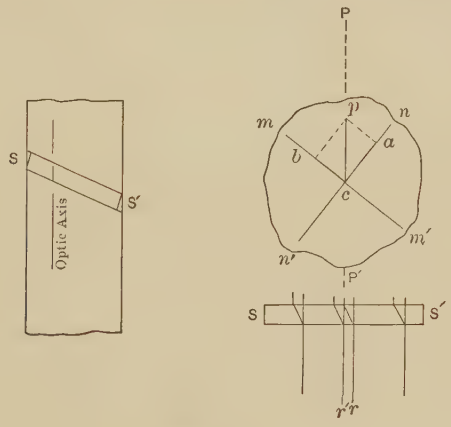

Fig. 50.

there start two components in the uniaxial crystal, one vibrating as an extraordinary, the other as an ordinary ray; the first in the plane of the optic axis, the second at right angles to it. The traces of these two planes are indicated as mm' and nn' on the horizontal projection of the crystal section. The ordinary component *o* is not refracted for normal incidence. The extraordinary component *e* is refracted as indicated in the figure. They would emerge at the surface of the plate at different points. But there is another incident ray, r', whose extraordinary component emerges at the same point on the upper surface as that from which the ordinary com-

ponent from the ray r emerges. And so, for every point on the upper surface of the plate, there emerge two components vibrating in planes at right angles to one another. From the point c, then, there emerge two rays, one vibrating in mm' and one along nn'.

Since the components o and e traverse different distances in the crystal, and also travel with different velocities, they execute a different number of vibrations in reaching the upper surface. They start at the lower surface in the same phase; they reach the upper surface in phases depending on the thickness of the plate, the difference in path of the ordinary and extraordinary rays, and the difference in their velocities. At the upper surface the phasal difference between the two rays may be zero, or a whole number of wave lengths, or some fraction of wave lengths, less or greater than unity.

The amplitude of each ray will depend on the position of the possible planes of vibration in the crystal with respect to the plane of vibration of the polarized light coming from the polarizer. In Fig. 50 let PP' be the direction of vibration of the light coming from the polarizer; mm', nn', the directions of the planes of vibration in the crystal. If cp represent the amplitude of the light from the polarizer, ca and cb will represent the amplitudes of the components vibrating in the planes mm' and nn' respectively.

If the crystal plate is rotated about a normal to its surface, the value of the amplitudes ca and cb vary. When mm' is parallel to PP', $ca=cp$ and $cb=0$; that is, all the light passes through the crystal vibrating in the plane mm'. When nn' is parallel to PP' the reverse is true. When mm' and nn' make angles of 45° with PP', $ca=cb$.

If the rotating plate be looked at with the unaided eye, no change in the total illumination is noted, nor is it possible to recognize what has taken place in the crystal or at its upper surface. The two rays, vibrating at right angles to one another upon emerging from the crystal, combine to produce a resultant vibration which may be plane polarized, elliptically or circularly polarized, according to the phasal difference between the two rays. The eye alone fails to recognize the character of the vibration, noting only the intensity.

If a second Nicol prism is placed between the eye and the crystal plate, the polarized light from the crystal is resolved again into two components, one of which is destroyed and the other transmitted, when its character and intensity can be noted. The upper nicol or analyzer may be turned at any angle with respect to the lower nicol, but in practice, the crossed position is that almost always employed. For this reason the phenomena to be discussed will be those

exhibited when the nicols are crossed. From this discussion it will be possible to understand the phenomena exhibited in any other position of the nicols.

In Fig. 51 let AA' be the direction of vibration of the light that passes through the upper nicol or analyzer. If the phasal difference between the two components vibrating in mm' and nn' is 0λ or λ, 2λ, etc., that is, if the vibrations are in like phases, when one is at its point of plus maximum elongation the other is also. They were in like phases when they entered the crystal plate, consequently the components ca and cd in Fig. 51 represent the condition of the vibrations upon leaving the upper surface of the plate.

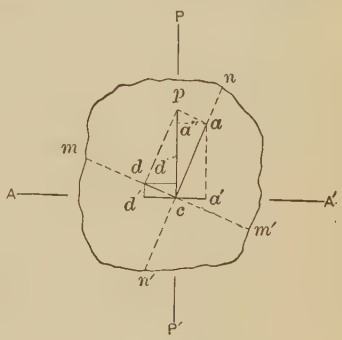

FIG. 51.

In actual fact these components combine in the isotropic medium between the crystal plate and the analyzer to produce some form of polarized vibration which is resolved into two again upon entering the upper nicol. In this particular case the resultant would be plane polarized light, vibrating parallel to PP'. But the result in the analyzer would be the same if the upper nicol were placed in immediate contact with the crystal plate, and the light passed directly from one to the other without passing through an isotropic medium (air). And, since the discussion of the phenomena is simplified by omitting the consideration of the composition and resolution taking place within the isotropic medium between the crystal plate and analyzer, it will be carried on as though the analyzer were in immediate contact with the plate.

Considering, then, each component, ca, cd, separately, upon entering the upper nicol ca is resolved into two components: ca'', vibrating in the plane of the light which is totally reflected and absorbed; ca', vibrating in the plane of that which can pass through. Similarly, cd is resolved into two components: cd'', which is absorbed in the analyzer; and cd', which can come through. But ca' and cd' vibrate in opposite directions, they counteract one another, and since they are always equal, whatever the angular position of mm', nn', with respect to PP', as shown in Fig. 52, the result is zero, no light. The triangles cap and cdp are equal, therefore $aa''=dd''$ and $ca'=cd'$.

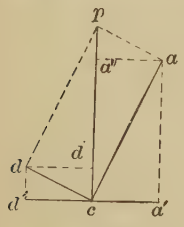

FIG. 52.

That is, with monochromatic light a parallel faced plate of uniaxial crystal placed between crossed nicols, when the phasal difference between the component rays leaving its upper surface is 0λ, λ, 2λ, etc., remains dark throughout a complete rotation of the crystal plate in the plane of its surface.

In case the phasal difference between the rays is $\frac{1}{2}\lambda$ or $\frac{3}{2}\lambda$, $\frac{5}{2}\lambda$, etc., when the vibration of one ray is at its plus maximum elongation, that of the other is at its minus maximum elongation. In Fig. 53, if *ca* is in its plus position, *cd* is in its minus position. Upon entering the upper nicol, *ca* is separated into two components: *ca''*, which is absorbed; *ca'*, which can pass through. Likewise *cd* is separated into *cd''*, which is absorbed; and *cd'*, which can pass through. Since *ca'* and *cd'* are in the same direction, the resultant motion is the sum of *ca'* and *cd'*. As before noted $ca' = cd'$. Upon rotating the crystal plate, as the inclination of *mm'*, *nn'* to *PP'* changes, the values of $ca' = cd'$ change. They are zero when *mm'* or *nn'* is parallel to *PP'*, and reach a maximum when the angle between *mm'* or *nn'* and *PP'* is 45°.

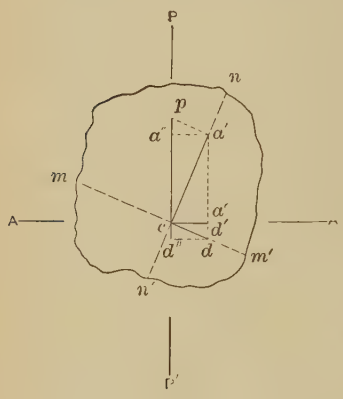

FIG. 53.

That is, with monochromatic light and crossed nicols, a plate of uniaxial crystal, from the upper surface of which the two component rays emerge with $\frac{1}{2}\lambda$, or $\frac{3}{2}\lambda$, $\frac{5}{2}\lambda$, etc., phasal difference, changes in illumination according to the angular position of the planes of vibration (*mm'*, *nn'*) with respect to the planes of vibration in the nicols (*PP'*, *AA'*). It is dark when the planes of vibration in the crystal are parallel to those in the nicols, and the illumination gradually increases from this position to that in which the planes of vibration in the crystal make an angle of 45° with those in the nicols. These positions are each passed four times in a complete rotation of the crystal plate.

In case the phasal difference between the components leaving the crystal is something other than a whole λ or a half λ, the components *ca'*, *cd'* in the plane *AA'* in the analyzer will not be equal to one another; consequently, there will always be some resultant vibration when the planes *mm'*, *nn'* are not parallel to *PP'*, *AA'*, in which case *ca'* and *cd'* will both be zero.

The resultant vibration will be least when the phasal difference is nearest a full λ. It will increase as the phasal difference approaches $\frac{1}{2}\lambda$ or some multiple of $\frac{1}{2}\lambda$.

In any one of these cases the amplitude of the resultant will be zero when the planes of vibration mm', nn' are parallel to PP', AA', and a maximum when these planes are 45° from one another. Consequently, in the case of any phasal difference between the emerging rays other than that of a λ or any whole number of λs, the crystal plate will be dark when the planes of vibration in it, mm', nn', are parallel to the planes of vibration in the crossed nicols, and it will have a maximum illumination when in the 45° position.

If, instead of monochromatic light, white light is transmitted through the crystal, the resultant interference will be a mixed color depending on the phasal differences of the various colors entering into the composition of white light. These colors are produced by wave motions whose length of wave ranges from 0.000380 mm. for ultra-violet to 0.000760 mm. for the *A* line in red. The number of different sizes of wave lengths between these extremes is very great, there being differences in the length of various waves of red, orange, yellow, green, blue, and violet. It happens, therefore, that the phasal differences between extraordinary and ordinary rays of all these wave lengths will grade from those that are whole λs to those that are $\frac{1}{2}\lambda$ or some multiple of $\frac{1}{2}\lambda$. The colors with a phasal difference of whole λs or nearly whole λs will be extinguished between crossed nicols, while those with phasal differences of half λs or nearly so will be strongest; consequently the color exhibited by the crystal plate will be made up of a portion of the component colors of white light whose phasal differences are nearest half wave lengths. The tone of this mixed color will not change with the rotation of the crystal plate, for the phasal differences will not be affected. But the intensity will vary from a maximum in the 45° position to zero, darkness, in the parallel positions.

Abnormal Interference Colors in uniaxial crystals may be brought about in several ways. The crystal may absorb part of the components of white light, producing a definite color, which not only gives color to the mineral, but also modifies the tone of interference colors by removing from the white light the components absorbed by the crystal. In the case of minerals with noticeable differences in the double refraction for different kinds of light, it may happen that the double refraction is zero for light of a particular wave length. For this color the crystal is isotropic, and such a color, and those

nearest it in the spectrum, would be cut out with crossed nicols, leaving the light of other parts of the spectrum to produce the interference colors. This is the case with vesuvianite, whose double refraction is low and variable, so that in one crystal it may be optically positive ($\varepsilon > \omega$) in one portion and negative ($\varepsilon < \omega$) in another. Moreover, the variation of double refraction for light of different wave lengths is such that in some crystals or parts of a crystal it is zero for blue, in which case the interference color is orange; or zero for green, when the interference color is reddish violet; or for yellow, when the interference color is indigo; when it is zero for red, the resulting color is blue. In melilite the double refraction is low, and, because it is often nearly zero for yellow, the interference color is indigo.

Since the phasal difference between extraordinary and ordinary rays emerging from a uniaxial crystal depends on the length of path traversed—thickness of plate—and on the relative velocities of the two rays, and since the relative velocities depend upon the character of the crystal and the direction in which the plate is cut from it, it follows that, for a plate cut in a certain direction through a crystal, the interference color varies with the thickness of the plate. If the plate is not uniformly thick, it will exhibit different interference colors in different places.

Quartz Wedge.—When a thin, plane faced wedge is cut from a quartz crystal, with one plane parallel to the optic axis, and this is placed between crossed nicols so that the planes of vibration in it stand at 45° to the planes of vibration in the nicols, the interference colors vary in a regular manner from the thin end of the wedge to the thick end. If the wedge were illuminated with monochromatic light, red, for example, and the extreme edge were of ideal thinness, there would be darkness at this place, because the path would be zero and there would be no phasal difference between the two rays. As the wedge thickens, the phasal difference increases from zero, and the red light is faint at first, increasing in strength until the wedge is thick enough to produce a phasal difference of $\frac{1}{2}\lambda$. Beyond this the red light decreases until the wedge is thick enough to produce a phasal difference of λ, when there is darkness, and so on; yielding alternate changes or bands of light and shadow grading into one another. The width of these bands depends on the steepness or flatness of the wedge. For light of shorter wave length than red the bands are narrower, beginning with darkness at the thin edge of the wedge. When white light is employed, the thinnest edge

of the wedge is dark, shading into gray-white followed by yellow, orange, and red. This grades through purple to blue, green, yellow, orange, and red, and so on, repeating the colors in the same order, over and over again. However, the tone of the successive colors of each order is not the same, since they are differently mixed. They are most like the spectrum colors near the thinner end of the wedge, becoming paler toward the thicker end, eventually becoming almost white. The successive orders of colors are called first, second, etc., beginning at the thin end of the wedge. Each order ends with red. These interference colors are the same as Newton's scale of interference colors, produced by reflection from the sides of thin wedge-shaped films of any isotropic medium. They are shown more or less correctly in the colored plate, at the end of the book, on which the limits of the several orders are indicated. For more detailed discussions of this scale of colors the student is referred to Groth's Physikalische Krystallographie, p. 39; Lévy and Lacroix's Minéraux des Roches, p. 49 et seq., and Rosenbusch and Wülfing's Mikroskopische Physiographie, Vol. I, Part I, p. 227.

Quartz wedges are prepared in some instances with the long axis of the wedge parallel to the optic axis of the quartz crystal. In other cases the optic axis is at right angles to the longer side of the wedge, while in others it is 45° to the longer side.

Crystal Plates in Various Positions.—Since the interference color exhibited by a crystal plate depends on the relative velocities of the extraordinary and ordinary rays, it follows that plates of the same kind of crystal of like thickness will exhibit different interference colors according to the crystallographic position of the plate. For plates of like thickness, with normal incidence, the greatest difference of velocities between the extraordinary and ordinary rays occurs in plates cut parallel to the optic axis; the least difference, zero, when the plate is cut at right angles to the optic axis, for then the light is transmitted parallel to the optic axis. The case is illustrated by a section of quartzite rock, in which crystals of quartz occur in various orientations between crossed nicols, the differences in interference in various crystals are shown in Fig. 54.

It is to be noted that a plate of a uniaxial crystal cut perpendicular to the optic axis, having no phasal difference between the component rays, remains dark between crossed nicols throughout a complete rotation of the plate for any and all colors; it behaves like an isotropic medium.

Strength of Double Refraction.—When plates of like thickness are placed between crossed nicols, the interference color varies with the differences in velocity between the extraordinary and ordinary rays in each crystal plate; but these differences of velocity correspond to differences in the double refraction of each plate in the direction in which the light has traversed it. Interference colors, then, are exponents of the strength of the double refraction in crys-

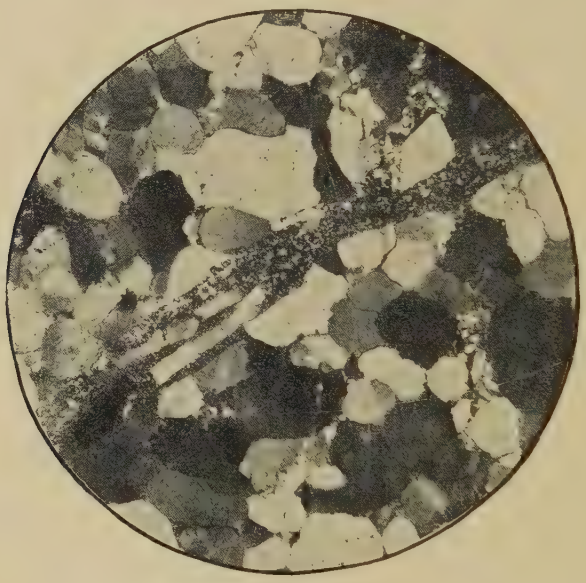

Fig. 54.

tals, and may be employed to determine the amount of double refraction.

For a known thickness of plate the interference color corresponds to a definite difference of refraction between the two rays, the actual index of refraction of the rays not being indicated. Thickness of the plate may be determined from the interference color when the double refraction of the crystal is known and the crystallographic position of the plate is also known. When several kinds of crystals occur by the side of one another, as in a rock section, and are of like thickness, it is possible to determine the double refraction of one crystal by using another whose double refraction is known as a means of determining the thickness of the plate. Quartz, whose double refraction is well known, serves as a convenient standard, on account of its frequent occurrence in rocks and the ease with which its optical

and crystallographic orientation may be determined. The maximum double refraction, $n_e - n_o = .009$, occurs in plates cut parallel to the optic axis. A colored diagram for the determination of double refraction by means of interference colors is given at the end of the book. It is the same as that employed by Michel-Lévy and Lacroix in their work on the minerals of rocks.[1] In order to use it for the determination of the double refraction of any given mineral, it is first necessary to find near it in a rock section a known mineral cut so as to exhibit its maximum double refraction, that is, parallel to the optic axis when the mineral is uniaxial, or parallel to the plane of both optic axes when the mineral is biaxial. Knowing the value of $\omega - \varepsilon$ or $\varepsilon - \omega$ in the first case, or of $\gamma - \alpha$ in the second, and noting the interference color exhibited by the mineral section, the thickness of the section is determined by observing in the colored diagram the point of intersection of the particular band of color with the diagonal line corresponding to the value of $\gamma - \alpha$. This may be assumed to be also the thickness of the neighboring mineral whose double refraction is to be determined. Observing, then, the intersection of a horizontal line, corresponding to the assumed thickness and the band of color representing the interference color in the mineral to be determined, the diagonal line passing through this point will indicate the strength of the double refraction of the mineral in question, for the particular orientation in which the thin section lies. It may not correspond to the maximum birefringence, $\omega - \varepsilon (\varepsilon - \omega)$ or $\gamma - \alpha$. This can only be determined when the mineral section is oriented parallel to one or two optic axes, as the case may be.

Use of the Quartz Wedge.—Determination of the Faster and Slower Ray and the Order of the Interference Color.—Since the interference color is the result of one component being ahead of the other some fraction of a period of vibration, that is, being faster than the other, and since by thickening a crystal plate the interference color is raised in the scale of colors, and by thinning it the color is lowered, it follows that by reducing the difference between the two components the interference color will be lowered in the scale, and by increasing the difference the color will be raised.

If one crystal plate be placed over another, so that the direction of vibration of the faster ray in one plate is parallel to that of the faster ray in the other plate, the gain of the faster ray in the first

[1] Les Minéraux des Roches, Paris.

plate will be increased by the gain of the faster ray in the second and the interference color of the combined plates will be due to the sum of the phasal differences between the fast and slow rays in each plate. On the other hand, if the plates be so placed that the faster ray in one plate vibrates parallel to the slower ray in the other plate, the gain made by the faster ray in the first plate is reduced by the loss of the slower ray in the second plate, and the resulting interference color is due to the difference between the phasal differences in the two plates. If the gain in one plate is equal to the loss in the other plate the resulting interference color is zero—darkness.

The quartz wedge may be used to determine the directions of vibration of the fast and slow rays in a crystal section by placing it over the section so that the planes of vibration in the quartz wedge and those in the crystal plate are parallel to one another, and observing the changes in interference color as the wedge is moved over the plate thin end first.

The planes of vibration should be in the 45° position between crossed nicols in order to obtain the maximum illumination. The directions of vibration in the crystal plate are found by rotating it until it becomes dark, when the directions of vibration must be parallel to the planes of vibration in the nicols, which planes are parallel to the cross hairs in the eyepiece of the microscope. The planes of vibration have been determined for the quartz wedge, and the direction of vibration of the slow ray is marked upon it, parallel to the optic axis.

As the wedge advances, if the interference colors move toward higher orders, the effect is that of thickening the plate, and like vibrations must be parallel to one another, that is, the direction of vibration of the slow ray in the wedge must be parallel to that of the slow ray in the crystal plate. If the colors descend in the scale the reverse condition must exist, the slow in the quartz must be parallel to the fast in the crystal plate. In this case the colors will pass to the lowest end of the scale and become darkness when the phasal difference in quartz wedge and crystal plate are the same but in opposite directions. Each would exhibit the same color if viewed by itself. In this position the color in the plate is said to be compensated by that in the wedge, which, for this reason, has been called a *compensator*.

In this manner, also, the order of color in the crystal plate is determined. It is the same as that in the quartz wedge in the position of compensation, and this is either indicated on the wedge or can

be determined by rotating the mineral plate until its planes of vibration are parallel to those in the nicols, when it would be dark, and noting the color of the quartz wedge by moving it toward the thin end and observing the changes of colors.

When there is a wedge-shaped edge to a crystal section having strong double refraction, there are bands of interference colors parallel to the edge of the wedge whose width depend on the inclination of the face of the wedge and the strength of the double refraction of the crystal. If the crystal is surrounded by an isotropic medium, or a double refracting one whose interference color is dark gray, then the order of the color on any part of the crystal can be determined by noting the bands of different colors from the thin edge to this place. It will be noticed that,when a quartz wedge is placed above such a wedge-shaped crystal in the 45° position and moved forward, the bands of color on the crystal move toward the edge of the crystal or away from it according as, in the first case, directions of like vibration, fast and fast, in the quartz wedge and in the crystal section are parallel to one another, or, in the second case, directions of unlike vibration, fast and slow, in the two minerals are parallel to one another. This movement of the color bands becomes a means of determining the direction of vibration of the fast and slow rays in a wedge-shaped mineral.

Combination Wedge.—Owing to the fact that it is not possible to prepare the thin edge of a quartz wedge so that it diminishes to an ideal vanishing point, in consequence of which extremely low interference colors, below that produced by a phasal difference of $\frac{1}{4}\lambda$, can not be compensated, a combination wedge has been devised by F. E. Wright[1] which furnishes a gradual transition of interference colors from those of about the third order to zero. This is accomplished by placing a wedge of quartz or of selenite upon a parallel-faced plate of selenite, of such a thickness that it yields a uniform interference color corresponding to that produced by the wedge near its middle. The selenite plate is oriented so that the directions of vibration of the fast and slow rays are parallel to those of the slow and fast rays in the wedge, so that the double refraction of the two minerals compensate one another about the middle of the wedge. At this place there is no phasal difference between the rays passing through the combination wedge, and there is darkness when the wedge is between crossed nicols. From the middle

[1] T. M. P. M., Vol. 20, 1901, p. 275, and Jour. of Geol., Vol. 10, 1902, p. 33.

of the wedge the interference colors rise in the scale toward the thicker end of it, and descend in the scale toward the thinner end.

Determination of the Amount of Double Refraction.—The quartz wedge may be used to determine the double refraction of any substance, by comparing the interference color exhibited by a section of the substance with the colors on the wedge, noting the thickness of the section, and making use of the diagram on the colored plate. The accurate determination of the interference color may be accomplished by means of a quartz wedge made to move along a graduated scale placed outside of the tube of a microscope. The colors from it are reflected from a prism within the microscope, and may be compared directly with those from the mineral section. The

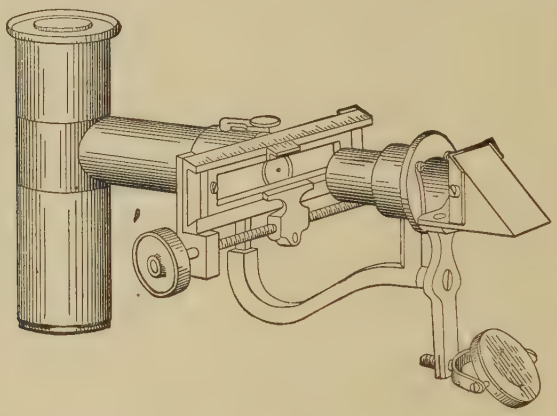

FIG. 55.

apparatus is known as a *Michel-Lévy comparator*, and is shown in Fig. 55. Still more exact determinations of the double refraction of a substance may be made by means of a Babinet compensator,[1] but this method is not applicable to the study of minerals in rock sections, since it necessitates an exact determination of the thickness of the section.

Selenite Plate.—For determining the fast and slow rays in plates or crystals with very weak double refraction, when the interference color is grayish white of the first order, a plate of selenite, gypsum, may be used to great advantage. The selenite is prepared so as to furnish a uniform purplish red of the first order. This tint, lying

[1] Described in Rosenbusch-Wülfing's Mikro. Phys., etc., Vol. I, Pt. I, p. 284.

between yellow and blue, is easily affected by the slightest change of double refraction or of the phasal difference between the two rays, changing to bluish purple and blue when the phasal difference is increased, and to reddish purple, orange, and yellow when it is decreased. It is for this reason called the *sensitive tint* (*teinte sensible* of the French).

It may be used also for detecting exceedingly weak double refraction, which may produce so slight a variation in the dark gray interference color as to escape detection. The change in tint of the purple of the selenite plate is much more noticeable.

Determination of the Directions of Vibration of Light Passing through Double-refracting Minerals.—The position of the planes of vibration of the two components of transmitted light in certain sections of birefringent minerals, is often a distinguishing characteristic, and its exact determination is for this reason important. As already pointed out, the complete extinction of light with crossed nicols occurs when the planes of vibration of the two components of transmitted light are parallel to the planes of vibration, or principal optical sections, of the polarizer and analyzer. In a petrographical microscope these directions are indicated by the positions of the cross hairs in the occular. Therefore, when a mineral plate is rotated so that there is total darkness, the directions of vibration in it are parallel to these cross hairs. But the position of maximum darkness is not always easily recognized, because the change of illumination is gradual, and there is commonly a range of several degrees through which the darkness appears equally deep. By turning the mineral plate back and forth through this range of angles, it is usually possible to approximate to the position of maximum darkness. And for many purposes this is sufficiently accurate, especially with the brilliant illumination which is obtained in some microscopes. When greater accuracy is required, one of several methods may be employed. They depend mainly on substituting changes of color for degrees of darkness.

Selenite or Quartz Plate.—If a plate of gypsum or of quartz, or any other colorless mineral, be of such a thickness as to yield a uniform purple interference color when placed between crossed nicols, in the 45° position, and this be placed between a birefringent mineral and the analyzer, the purple color appears whenever the planes of vibration of the underlying mineral are parallel to the principal planes in the nicols. A slight deviation from this position will produce a noticeable change in the color of the superimposed plate,

which will become a more bluish or more reddish purple. Such a change is more readily detected when a portion of the field remains a constant purple color, that is, when the field is not wholly occupied by the mineral section, but is partly an isotropic medium, such as balsam, glass, or an isotropic mineral.

Klein's Quartz Plate.—A similar result is obtained by using a thick plate of quartz, cut perpendicular to the optic axis and exhibiting rotary polarization. When placed between crossed Nicols, the color obtained will depend on the angular position of the analyzer, and can be chosen to suit the color of the mineral under investigation. For a colorless section, the sensitive violet tint may be used as with the selenite plate. For colored minerals some other interference color may be used, according to the case.

Bertrand Ocular. — A still more sensitive method makes use of contrasted colors in sharply defined quadrants of the microscopic field. This is accomplished by means of an ocular in which four pieces of quartz cut perpendicular to the optic axis are introduced. Two are from a right-handed crystal and two from a left-handed one. These are cut thick enough to exhibit rotary polarization, and are of the same thickness, so as to exhibit the same color between crossed nicols. They are shaped as quadrants, so that the boundary edges between them correspond to the cross hairs. The right-handed quartzes are placed in diagonally opposite quadrants (Fig. 56). When the nicols are crossed, the four quadrants are the same color. If a colorless mineral section beneath this ocular is oriented so that the planes of vibration are parallel to the principal planes in the nicols it will not change the color of the quartz quadrants; but, if slightly rotated, the colors of the overlying quartz in adjacent quadrants will be different, those in diagonally opposite quadrants being the same.

FIG. 55.

Calderon's Ocular is similar to Bertrand's in contrasting adjacent interference colors, but is less sensitive. It consists of two plates of calcite placed in juxtaposition along a plane which serves as a plane of optical symmetry for somewhat inclined pieces cut from a calcite crystal. The plane of contact also marks the direction of a principal optical section in one of the nicols. The pieces of calcite are prepared by cutting a crystal perpendicular to a cleavage-plane and parallel to the shorter diagonal of the traces of the other planes of cleavage, that is, in a principal optical section. Each piece is then cut at a similar inclination to this plane, and joined together.

The artificial twin is then cut into a plate at right angles to the plane of contact and placed in the focus of an ocular. When between crossed nicols the two halves of the Calderon ocular are equally illuminated. A mineral section between the ocular and the polarizer affects both halves of the calcite plate alike when its planes of vibration are parallel to the principal sections of the nicols. When revolved slightly from this position, it produces different illumination in the overlying parts of the two pieces of calcite.

Measurement of Extinction Angles.—The angles made by the planes of vibration of the componets of transmitted light with a particular crystallographic direction in a mineral section are known as the angles of extinction, or the *extinction angles*. It is only necessary to note one of these two angles, as their sum is always 90°. Ordinarily it is the smaller angle that is measured and recorded. The crystallographic direction from which the angle is measured is commonly the trace of a crystal plane, as of a face, a cleavage crack, or a twinning or composition plane. The method of measuring an extinction angle is to rotate the crystal section until the particular crystallographic line is parallel to one of the principal planes in the nicols which are indicated by the cross hairs in the ocular of the microscope, the angular position of the stage being noted by means of the vernier. The stage and mineral section are then rotated until one of the planes of vibration in the mineral is parallel to the same plane as that to which the chosen crystallographic line was parallel. This position is indicated by the complete extinction of the transmitted light, and may be determined by any of the methods described in the preceding paragraphs. The angle of rotation is read from the circumference of the stage. If the angle is greater than 45°, the supplemental angle is recorded, unless it is desired to note the angle to a particular one of the two directions of vibration, as to that of the faster component, or of the slower one, as the case may be.

Conoscope.—In addition to the real or virtual image of an object which is produced by the focussing of light from all points of the object by means of a lens or microscope, there are other optical phenomena due to the focussing of rays of light transmitted through crystals that do not yield an image of the crystal itself, but, when polarized light is used, present an assemblage of interference colors which has been called an *interference figure*.

The phenomena will be understood by considering that the light transmitted from a distant source through a crystal consists of

parallel rays which may constitute the whole beam of transmitted light, or may form small beams which together constitute a converging bundle of small beams. Such parallel rays, upon passing through a thin-edged lens, converge at the real foci, f, f', f'', on the other side of the lens (Fig. 57), which are more distant than that of the real image of the crystal through which the light has passed. If the transmitted light consists of a bundle of converging small beams of parallel rays, the real foci, f, f', f'', of the several beams will not lie in a plane, but will be on a spherical surface corresponding to the curvature of the lens or mirror supplying the converging light. At this place there will be no image of the crystal itself. There may be an image of the source of light.

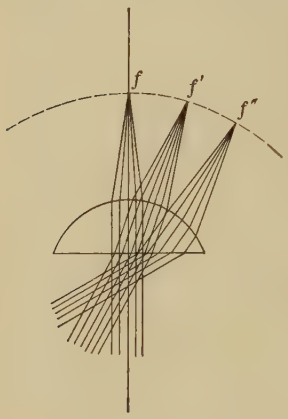

FIG. 57.

This corresponds to the focus of a telescope whose purpose is to observe distant objects or sources of light. The first telescopic image or focus may be reproduced as a real or virtual image by means of other lenses properly adjusted, but it is evident that in a microscope the lenses which are properly placed to magnify the real image of the crystal section will not be in the proper position to focus on the first telescopic image which is more distant from the objective lens than the image of the crystal. The first telescopic image may be seen above the objective of the microscope when the ocular is removed. A second telescopic image, smaller than the first, may be seen at some distance above the ocular when this is in place. Or an enlarged virtual image of the telescopic image may be obtained by inserting a properly adjusted lens between the ocular and objective. This is known as an Amici-Bertrand lens; its position in the microscope is indicated at K in Fig. 13, p. 109. The telescopic image employed in petrographical work is produced by the interference of polarized light that has been transmitted through a crystal as a converging bundle of small beams of parallel rays, and on this account the apparatus or arrangement of lenses employed is called a *conoscope*. A petrographical microscope may be converted into a conoscope by removing the ocular or introducing an Amici-Bertrand lens. In most cases it is necessary to use the strongly converging lens in the stage below the crystal, and also to employ a wide-angled objective lens. The further discussion of the conoscope will be found in

connection with that of the interference phenomena in converging light.

Behavior of Plates of Uniaxial Crystals between Crossed Nicols in Convergent Light.—The phenomena exhibited by plates of uniaxial crystals in a parallel beam of plane polarized light do not reveal the direction of the optic axis in the crystal. This is done by using convergent polarized light in a conoscope as follows: let the crystal plate be cut perpendicular to the optic axis (Fig. 58), and let a

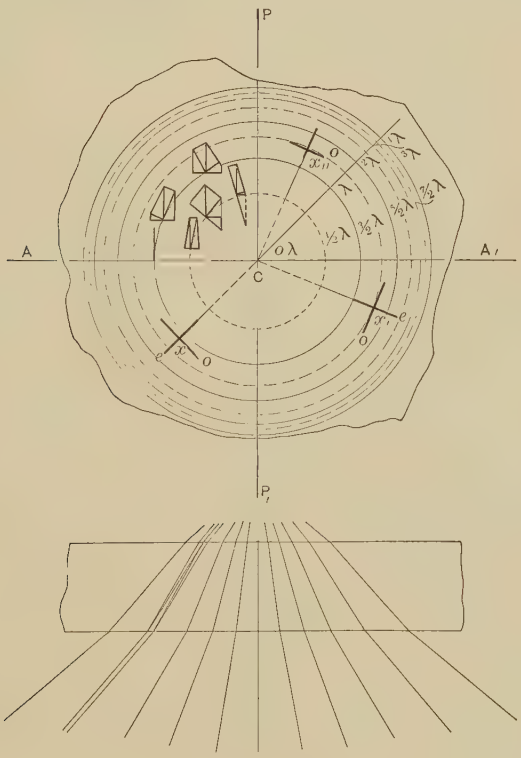

Fig. 58.

converging bundle of small beams of polarized light pass through it so that the axis of the cone is perpendicular to the plate and the plane of vibration of the light is parallel to the line PP'. Let AA' be the direction of the vibrations that pass through the analyzer.

For every ray of incidence there are two components in the crystal plate, differently refracted and having different velocities. The extraordinary ray vibrates in a plane passing through the ray and the optic axis. The ordinary ray vibrates at right angles to this

plane. At every point on the upper surface of the crystal plate there will emerge two components of the parallel rays in any one small beam; these will have a phasal difference of vibration depending on the inclination of these rays to the optic axis and on the length of path traversed in the crystal. Since the rays have the position of elements in a solid cone, all those making the same angle with the axis will lie in a conical surface about the axis. At any points, x, x', x'', etc., on the surface of the plate there will emerge two rays, the extraordinary ray (e) vibrating in a plane whose trace is cx, cx', cx'', etc., and an ordinary ray (o) vibrating at right angles to cx, cx', etc.

Along the center, or axis, of the cone of light the two rays emerging at c will have no phasal difference. The spot c will be dark. The components which travel nearly parallel to the axis will have a very slight phasal difference. Proceeding outward the two components will have more and more of a phasal difference the greater their inclination to the axis. At some angle the phasal difference will be one wave length for monochromatic light, for example, a particular red. When these rays emerge from the plate there will be darkness, no matter what angle the planes of vibration make with the planes of vibration in the nicols. Consequently, there will be a cicle of points about the axis of the cone c, from which the two components having a phasal difference of one wave length (λ) will be extinguished in the upper nicol, resulting in a dark ring about the center dark spot. At the distance from the center at which the components have a phasal difference of two wave lengths (2λ) there will be a second dark ring, and so on. The rings will be closer and closer together outward from the axis, because the inclination of the rays and the length of path in the crystal plate traversed by the light increase with the distance from the axis. The rate, of course, depends upon the angle of convergence of the rays; the rings are closer together the larger the angular aperture of the lenses employed. This is evident from Fig. 59, in which the diverging lines represent the directions along which the phasal differences are 0λ, 1λ, 2λ to 6λ, the inclinations to the axis of the conoscope being approximately 10°, 18°, 24°, etc. The interference figure produced by a lens whose angular aperture is 10° is represented by a; that produced by a lens of 30° aperture by b; and that by one with 60° aperture by c. The diameter of the field in each case is represented as the same. This, however, is not correct, since it is much smaller for the lens with the larger angular aperture.

Other things being equal, the distance of the rings from the center varies with the wave length of the light. They will be smaller circles for blue light than for red.

At the distance from the center at which the component rays emerge with phasal difference of half a wave length, there will be a

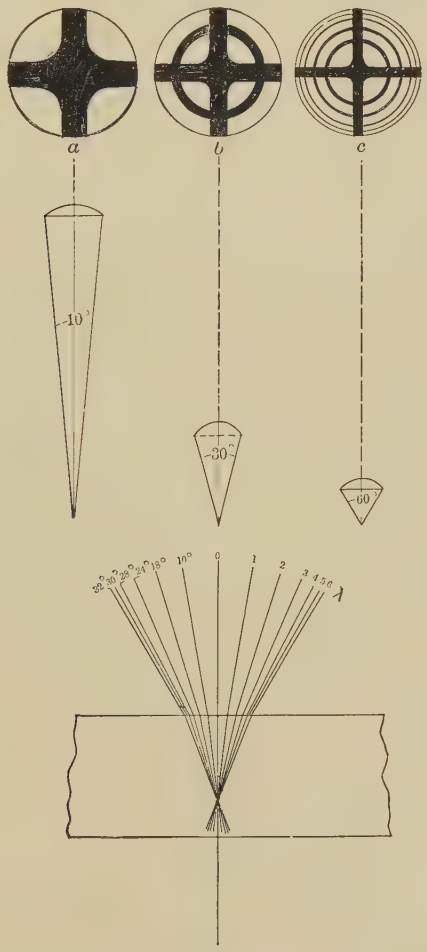

FIG. 59.

maximum of light when the planes of vibration are 45° to the planes of vibration in the nicols. The illumination will vary with the positions of vibration, until it will be zero where these are parallel to the planes of vibration in the nicols, PP' AA'. That is, in a circle covering the points having like phasal differences, $\frac{1}{2}\lambda$, there will

be four points of maximum illumination lying in the middle of the quadrants made by the lines PP' and AA', and four points of darkness where the circles cross these lines, PP' and AA'. The same is true to a lesser degree for component rays whose phasal differences are between $\frac{1}{2}\lambda$ and 0 or λ. In each circle there will be a maximum of light in the middle of the quadrants and darkness where the circles cross PP' and AA'. This is also the case for component rays whose phasal differences lie between λ and 2λ, and so on.

It follows from this, that in monochromatic light there will be concentric circles of darkness (Fig. 60) with spaces of light between, which are brightest in the middle of the quadrants and pass into darkness in lines along PP' and AA'. These lines form a dark cross,

Fig. 60.

whose arms are parallel to the directions PP', AA'. The rings and cross form an *interference figure* at the real focus of the objective lens of the conoscope. With white light the concentric rings are no longer dark, but colored, with mixed colors like those exhibited by a quartz wedge, and for the same reason. Commencing with darkness at the center, the colors follow one another outward through successive orders. The arms of the cross remain dark, without color, because all the component rays of white light are extinguished when they vibrate in planes parallel to the planes of vibration in the nicols, no matter what their wave length or phasal difference.

When the optic axis is exactly parallel to the axis of the cone of converging rays, the position of the rings and of the cross does

not shift if the crystal plate is rotated about the optic axis. It remains stationary. If, however, the plate is cut at an inclination to the optic axis, the ray whose components travel parallel to the optic axis will not be in the axis of the cone of converging light, but will emerge to one side of the center of the field of view. The interference figure will resemble closely that produced by a plate perpendicular to the optic axis; there will be a dark cross with concentric rings which are almost circles. The center of the cross marks the point of emergence of the ray traveling parallel to the optic axis in the crystal plate. When the plate is rotated about the axis of the cone of converging light, the inclined optic axis describes a

FIG. 61.

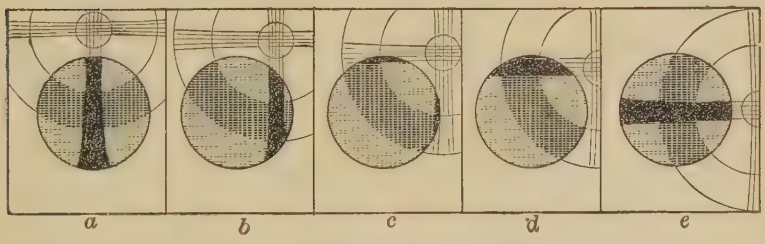

FIG. 62.

hollow cone about the axis of rotation, and the center of the dark cross in the interference figure describes a circle about the center of the field of view. The arms of the cross move parallel to themselves, remaining parallel to the directions PP' and AA' in the nicols. The colored circles shift with the center of the cross (Figs. 61 and 62, after Lévy and Lacroix). If the section is cut parallel to the optic axis, the interference figure resembles that of a biaxial crystal cut perpendicular to an obtuse bisectrix, the obtuse angle in this case reaching the upper limit, 180°. Conversely, a biaxial crystal cut perpendicular to an acute bisectrix furnishes an interference figure resembling that of a uniaxial crystal cut perpendicular to the optic

axis when the acute angle approaches its lower limit, 0°. This will be understood after the discussion of biaxial interference figures (p. 173 et seq.).

Determination of the Optical Character of Uniaxial Crystals.—The uniaxial interference figure may be employed to determine the positive or negative character of a uniaxial crystal. This is accomplished by determining whether the extraordinary ray is slower or faster than the ordinary ray. If a thin plate of mica be placed over the uniaxial plate so that the directions of vibration in the mica lie in the 45° position with respect to the crossed nicols (Fig. 63),

FIG. 63.

the slow component, s_m, in the mica will be parallel to the extraordinary rays in one diagonal 45° line through the interference figure, and the fast component, f_m, in the mica will be parallel to the ordinary rays along this diagonal. The direction of vibration of the slow rays in the mica is usually marked by an arrow on the mica plate, and the mica is thinned until the phasal difference between the slow and fast components after passing through it is one quarter of a wave length ($\frac{1}{4}\lambda$) approximately.

Let us consider the case of an optically positive mineral. The extraordinary ray is slower than the ordinary. Along the diameter through the center of the interference figure which is parallel to the arrow in the mica plate, the extraordinary rays leave the crystal plate some phases behind the ordinary rays. At the center, however, the two emerge with no phasal difference, but, on passing through the mica plate, they acquire a difference of $\frac{1}{4}\lambda$; and, vibrating at 45° to the planes of vibration in the nicols, yield an interference color.

From the center along the diameter mentioned, the phasal difference between the two rays at each point is increased by $\frac{1}{4}\lambda$ on passing through the mica plate, because the directions of vibration of the slow rays in both media are parallel to one another. At the point where the phasal difference for the crystal plate is $\frac{3}{4}\lambda$, it will be 1λ after passing through the mica. The position of the first dark circle will move toward the center to this spot. Similarly, the second dark circle will move inward to where the phasal difference in the plate is $1\frac{3}{4}\lambda$, for this becomes 2λ after passing through the mica plate, and so on for each circle in succession in this quadrant of the interference figure. The same thing will take place for the circles in the opposite quadrant traversed by the arrow of the mica plate. Each circle will move toward the center. These quadrants will behave as though the crystal plate were thickened.

The behavior in the other two quadrants will be directly the opposite, for the diameter of the interference figure at 45° to the planes of vibration in the nicols is at right angles to the direction of vibration of the slow rays in the mica, marked by the arrow. It is parallel to the direction of vibration of the fast ray in the mica. But this diameter is the trace of the plane of vibration of the extraordinary rays in the crystal plate, the slow rays; consequently, the phasal differences between the two rays leaving the crystal plate at every point along this diagonal are reduced $\frac{1}{4}\lambda$ when the rays pass through the mica. At the point where the difference is $\frac{1}{4}\lambda$ upon leaving the plate it is 0λ upon leaving the mica, that is, there is a dark spot at this point. The first dark circle will occur where the phasal difference on the crystal plate is $1\frac{1}{4}\lambda$, for this becomes 1λ upon leaving the mica, and so on. The dark rings move outward from the center. The same is true of the dark rings in the opposite quadrant. They move outward, and a dark spot appears to one side of the center. The two dark spots lie opposite one another across the direction of the arrow. A line connecting them makes with the line of the arrow the sign plus, +. The arms of the cross disappear.

For this case the optical behavior may be stated in general terms as follows: when a mica plate is placed over a section of a positive uniaxial crystal in the path of an interference figure the colored rings contract in the quadrants parallel to the direction of the arrow on the mica plate, and expand in the quadrants at right angles to the arrow, two dark spots appearing in these quadrants.

If the crystal is optically negative, the behavior of the colored

rings and dark spots will be the opposite of that for an optically positive crystal. The rings will contract in the quadrants at right angles to the direction of the arrow on the mica plate, and they will expand in the other two quadrants. The dark spots will lie in the quadrants parallel to the direction of the arrow, and a line connecting these two spots will make with the direction of the arrow the sign minus, $-$.

If the plate is cut at such an inclination to the optic axis that the center of the cross and rings lies outside of the field of the microscope, it is still possible to apply the method just described for determining the optical character of the crystal. By rotating the plate until one quadrant only of the interference figure occupies the field of view, and noting the location of the center of the figure by the curvature of the rings or the position of the arms of the cross, the behavior of the visible portion of the interference figure with respect to the mica plate will have the same significance as if the whole figure were visible. The location of one dark spot or the shifting of the color bands, or a portion of one, will show whether in the quadrant visible there has been expansion from or contraction toward the center of the figure.

Another method of determining the optical character of a uniaxial crystal may be employed in case the interference figure can not be obtained. It rests upon a determination of the direction of the optic axis, and of the relative velocity of the extraordinary ray as compared with that of the ordinary ray. The position of the optic axis may be determined by the appearance of the interference figure in a section cut parallel to the optic axis, to be described later (p. 177). Or it may be determined by the shape of the crystal. If prismatic, the optic axis will be parallel to the prism axis. The extraordinary ray vibrates in a plane passing through the optic axis, and in parallel plane-polarized light the relative velocities of the extraordinary and ordinary rays can be determined by means of the quartz wedge or selenite plate in the manner already described on page 145.

Rotary Polarization.—Some crystals have the ability to resolve plane-polarized light into two circularly polarized components, vibrating in opposite directions and traveling at different velocities. This usually takes place in a particular direction in the crystal, as in the direction of the optic axis in quartz. Upon leaving the crystal, the circularly vibrating components combine to form plane polarized light whose direction of vibration is determined by the relative veloci-

ties of the circular components and by the thickness of the crystal plate. It is also different for different kinds of light, so that plane polarized white light is dispersed when it undergoes rotary polarization. However, the dispersion, or the amount of rotation of the plane of vibration, is so slight in thin sections of those rock minerals that exhibit this phenomenon that it is not noticeable in rock sections, and consequently will not be considered in greater detail in this connection.

Indicatrix.—Index Surface of a Uniaxial Crystal.—In order to comprehend the optical behavior of biaxial crystals, it is necessary to consider more closely certain relationships between the velocities of transmission and the indices of refraction for extraordinary and ordinary rays in uniaxial crystals. As previously pointed out, the index of refraction of a wave motion is inversely proportional to its velocity of transmission: $n=\frac{C}{v}$. In a uniaxial crystal the velocities of transmission of light vibrating as extraordinary rays vary within a principal optic section as the radii vectores of an ellipse whose major and minor diameters are proportional to the maximum and minimum velocities.

All principal optic sections being alike in a uniaxial crystal the wave surface of the extraordinary rays is an ellipsoid of rotation. Through such an ellipsoid of rotation, all rays traveling at any given angle to the axis of rotation—the optic axis—will travel with like velocities and will have a constant index of refraction, which is the reciprocal of the velocity.

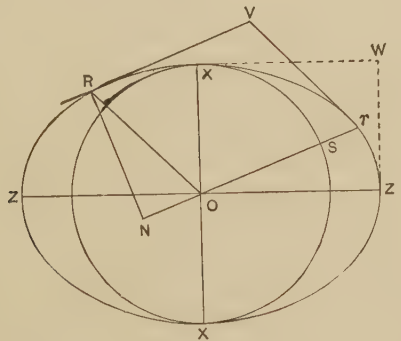

FIG. 64.

In Fig. 64 let the ellipse represent a section through the axis of rotation of the ellipsoid and *OX* be the direction of the optic axis, axis of rotation. *OZ* and *OX* are radii along the major and minor

axes. If the maximum index of refraction be designated by γ, and the minor index by α, then $OX=\alpha$, $OZ=\gamma$.

For a radius Or, which also represents the direction of transmission of two rays of light, it is possible to deduce from certain geometrical relations connected with the properties of an ellipse the velocity of the light vibrating as an extraordinary ray, and also of that vibrating as an ordinary ray. It is known that the area inclosed by the tangents at the extremities of conjugate diameters is a constant quantity. Therefore the areas inclosed by the tangents and conjugate radii are always equal. The conjugate radius to Or is parallel to the tangent to the ellipse at r. It is OR in Fig. 64. Therefore the area $OrVR=OZWX$ or $RN.Or=OZ.OX=C$, a constant. Hence $RN=\frac{C}{Or}$, $OZ=\frac{C}{OX}$.

That is, if OX is the minimum index of refraction, OZ, which is inversely proportional to it, corresponds to the velocity which is a maximum. The line OZ is the direction of transmission, and also represents the velocity of a ray which would vibrate in OX and have an index of refraction equal to OX. Similarly, the line OX is the direction of transmission and velocity of a ray which would vibrate in OZ and have an index of refraction equal to OZ.

From the expression $RN=\frac{C}{Or}$ we see that RN and Or bear a reciprocal relation to one another as index of refraction and velocity. That is, if Or represent the velocity of an extraordinary ray traveling in the direction Or, then RN will represent the index of refraction. Since the extraordinary ray vibrates in the plane of the optic axis and perpendicular to the direction of transmission, the line RN will also be the direction of vibration of the extraordinary ray, Or.

For any point, R, on the surface of an ellipsoid of rotation, or index surface, a ray, Or, may be found by passing through the center of the ellipsoid a line perpendicular to RN, the normal to the surface of the ellipsoid at R. Then the line RN will be the direction of vibration and the index of refraction of an extraordinary ray traveling along Or.

If the point R is at X, the ray Or coincides with OZ, and its index of refraction, RN, is equal to OX. If the point R is at Z, the ray Or coincides with OX, and its index of refraction is OZ.

When the point R is at X, it is possible to pass many lines through the center perpendicular to the normal, RN, for this passes through

the center. That is, in all directions in a plane perpendicular to RN, equal to OX, there are rays, traveling with like velocity $\left(OZ=\frac{1}{OX}\right)$ and vibrating in the direction OX. These rays would produce a circular wave front, corresponding to the circular equatorial section of the ellipsoid of rotation, the wave surface for extraordinary vibrations.

In like manner when the point R is at Z, the normal RN passes through the center, so that many rays may be passed through the center perpendicular to this normal, $RN=OZ$. All of these rays in a plane perpendicular to OZ will travel with the same velocity, $OX=\frac{1}{OZ}$. Since they all vibrate in the direction of OZ, perpendicular to the optic axis OX, they are ordinary rays. Their wave front is a circle. The same statement applies to all points, R, on the equatorial circle about the index surface. For each point, R, on the equatorial circle, there is a plane of rays vibrating in a line, RN, connecting the points, R, with the center of the ellipsoid, these rays traveling with constant velocity $\left(OX=\frac{1}{OZ}\right)$ and yielding a circular wave front. All of them together yield a spherical wave front representing the wave surface of the ordinary rays.

Thus it appears that from the index surface of a uniaxial crystal may be deduced, by the method of reasoning just employed, the wave surfaces for the extraordinary and ordinary rays.

In an isotropic crystal, since the index of refraction is the same for all directions of transmission, the index surface is a sphere, which is a limiting case of the ellipsoid of rotation, when the major and minor axes of the ellipse become equal.

Triaxial Ellipsoid.—In all other crystals than isotropic and uniaxial ones, the indices of refraction vary in such a manner with the direction of transmission of light that the index surface is a triaxial ellipsoid, that is, it is no longer a form made by rotation, but there are three axes of different values at right angles to one another, so related that any two considered together form the major and minor axes of elliptical sections through the center of the ellipsoid. These three section planes are perpendicular to one another. One axis, OX, represents the minimum index of refraction, α, Fig. 65; another, OZ, at right angles to it represents the maximum index of refraction, γ. The third axis, OY, perpendicular to the first and second, is intermediate in value, β. These axes, X, Y, Z, at right

angles to one another, are called the principle axes of the ellipsoid, and correspond to the principle indices of refraction in the crystal, α, β, γ ($\alpha < \beta < \gamma$). Some of the geometrical characters of a triaxial ellipsoid are: that the three planes passing through pairs of the principal axes, X, Y, Z, divide the ellipsoid symmetrically. Each is a plane of symmetry for the ellipsoid. Further, all sections cut by planes passing through the center of the ellipsoid are ellipses; in two positions the ellipses having all the diameters equal, that is, being circles.

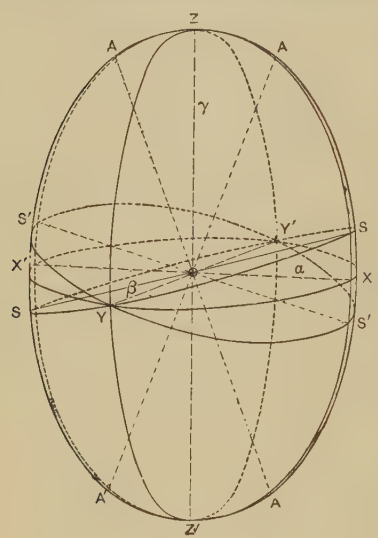

FIG. 65.

The circular sections must pass through the intermediate axis, Y, and be perpendicular to the plane of XZ. For if a plane, cutting sections from the ellipsoid, be rotated about the axis Y, it will furnish elliptical sections whose longer axis will be Z when it passes through Z. Upon rotation toward X the longer axis diminishes gradually in length until it becomes the shorter axis when the plane passes through X, consequently, there must be a position between Z and X at which the axis in the plane ZX equals the intermediate axis Y. In this position the elliptical section becomes a circle, SS in Fig. 65. The same statement applies to a plane rotating in the other angle between Z and X. There must be another position in which there is a circular section. These two positions must be symmetrically placed with respect to a plane passing through Y and X, and also to a plane passing through Y and Z.

These circular sections are somewhat analogous to the circular equatorial section in the ellipsoid of rotation in uniaxial crystals, which is perpendicular to the optic axis. The normals, A, A', to the two circular sections in the triaxial ellipsoid are also called *optic axes* and, for reasons to be explained later, they are the *primary* optic axes. They lie in the plane passing through X and Z, which is called the *plane of the optic axes*. The optic axes lie in the plane of the greatest and least axes of the triaxial ellipsoid. Crystals of this kind are called *biaxial crystals*.

The inclination of the circular sections, and consequently the angle between the optic axes A, A', depends upon the relative values of α, β, γ. For when β is much nearer in value to α than to γ, OY is nearly equal to OX, and the section plane rotating about Y would not move far from OX before encountering a radius of the ellipse $XZX'Z'$ equal to OX. As β approaches α in value the circular section approaches the plane of YX, and coincides with it when $OY=OX$ ($\beta=\alpha$). The triaxial ellipsoid passes into an ellipsoid of rotation with OZ the axis of rotation. The optic axes A, A', normal to the circular sections, approach one another as the circular sections approach the plane $YZY'Z'$. They become one optic axis when $OY=OX$ ($\beta=\alpha$).

In like manner, when the value of β is nearer that of γ than that of α, OY is nearer OZ, and the circular sections approach the plane $YZY'Z'$. The optic axes approach the axis OX. When $\beta=\gamma$, $OY=OZ$, the circular sections coincide with the plane $YZY'Z'$, and the optic axes coincide with the axis OX. The ellipsoid becomes one of rotation about OX, which is the optic axis.

The axes of the ellipsoid OZ and OX bisect the angles between the optic axes A, A'. That in the acute angle is called the *acute bisectrix;* that in the obtuse angle, the *obtuse bisectrix.*

The three principal axes of the ellipsoid will be designated X, Y, Z, in subsequent discussions and descriptions, instead of $\mathfrak{a}$, $\mathfrak{b}$, $\mathfrak{c}$, commonly used. These letters are easily confused with a, b, c, which indicate the crystallographic axes of a crystal.

When Z ($=\gamma$) is the acute bisectrix, by analogy with uniaxial crystals the biaxial crystal is said to be *positive,* for in the limiting case when the acute angle becomes zero the ellipsoid becomes a prolate ellipsoid of rotation, which is the positive uniaxial case.

When X ($=\alpha$) is the acute bisectrix, the biaxial crystal is said to be *negative.* When the acute angle becomes zero, the ellipsoid passes into an oblate ellipsoid of rotation, the negative uniaxial case.

The exact relation between the angle between the optic axes and the values of α, β, γ is given by the expression

$$\tan V = \sqrt{\frac{\frac{1}{\alpha^2} - \frac{1}{\beta^2}}{\frac{1}{\beta^2} - \frac{1}{\gamma^2}}}$$

where $2V$ equals the angle between the optic axes.

Transmission of Light through Biaxial Crystals.—The behavior of light in passing through a biaxial crystal is more complex than its passage through uniaxial crystals, because of the greater variability in the velocities of transmission as indicated by the variations in refraction with changes of direction. The wave surface for light radiating from a point within a biaxial crystal and the interference phenomena exhibited between crossed nicols are best understood by considering the triaxial ellipsoid as indicatrix of the refraction.

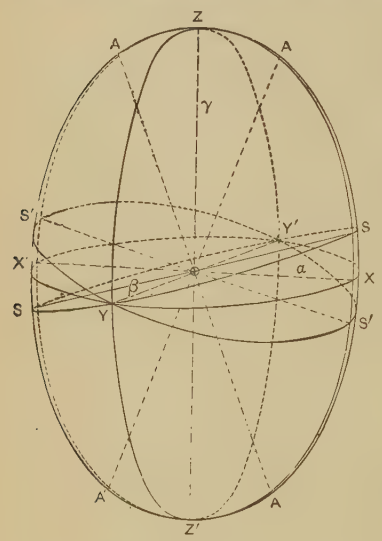

FIG. 65.

In Fig. 65 let the triaxial ellipsoid be the indicatrix of a crystal whose principal indices of refraction, α, β, γ, are proportional to OX, OY, OZ. The circular sections are represented by YSY' and $YS'Y'$; the principal optic axes by AA, $A'A'$.

The wave surface produced by the double set of plane polarized rays radiating in all directions, each pair of rays vibrating in planes at

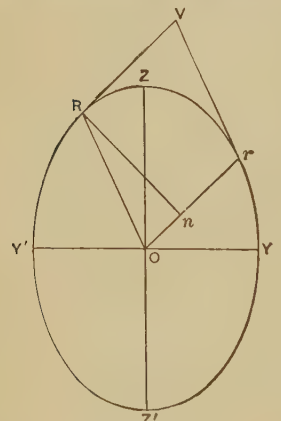

FIG. 66.

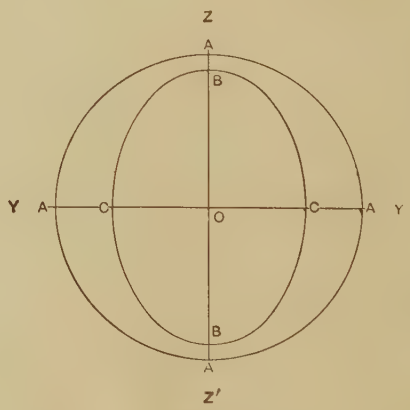

FIG. 67.

right angles to each other, may be developed from the indicatrix in the manner already employed in the case of uniaxial crystals.

In the plane $ZYZ'Y'$, Fig. 66, for any point, R, on the surface of

the ellipsoid there is a ray, Or, at right angles to Rn the normal to the surface of the ellipsoid at R. This ray lies in the plane $ZYZ'Y'$, because the normal Rn lies in this plane, since the plane divides the ellipsoid symmetrically and a tangent to its surface at R must be perpendicular to the plane of symmetry through that point. The ray Or vibrates parallel to Rn in the plane $ZYZ'Y'$, and the velocity of transmission is the reciprocal of Rn. Consequently the wave front for these rays in $ZYZ'Y'$ is an ellipse as shown in Fig. 67. In the direction of the axis OZ the ray travels with a velocity $OB = \frac{1}{OY} = \frac{1}{\beta}$. In the direction OY it travels with a velocity $OC = \frac{1}{OZ} = \frac{1}{\gamma}$. The velocities in other directions are as the radii vectores of an ellipse whose major and minor axes are OB and OC.

In all directions in the plane $ZYZ'Y'$ there are rays vibrating at right angles to this plane, for there is a normal to the ellipsoid which is

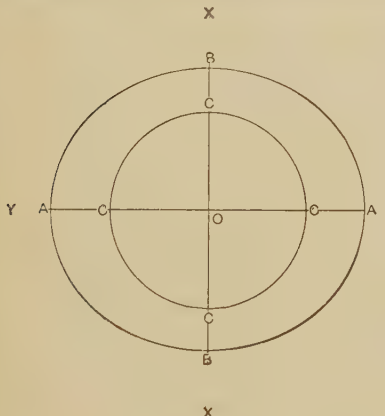

Fig. 68.

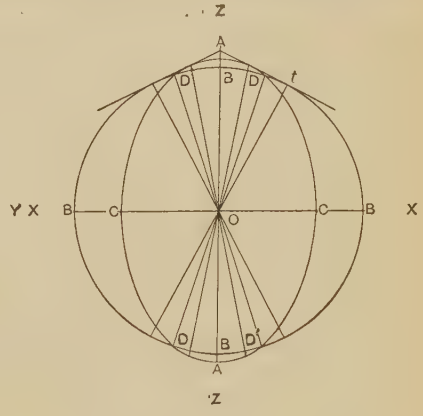

Fig. 69.

perpendicular to all of these rays at the center. It is in the axis OX. The rays vibrating parallel to the axis OX travel with like velocities, $OA = \frac{1}{OX} = \frac{1}{\alpha}$. The wave front is a circle which lies wholly outside the elliptical wave front.

In like manner in the plane $YXY'X'$ for any point, R, on the surface of the ellipsoid there is a ray, Or, at right angles to Rn, the normal to the ellipsoid at R. This ray lies in the plane $YXY'X'$, because the normal Rn lies in it, for it is a plane of symmetry for the ellipsoid, and the tangent plane at R is at right angles to it. The ray vibrates in the plane $YXY'X'$, and the wave front is an ellipse as

shown in Fig. 68. In the direction OY the ray travels with a velocity $OA = \frac{1}{OX} = \frac{1}{\alpha}$. In the direction OX it travels with a velocity $OB = \frac{1}{OY} = \frac{1}{\beta}$. For other directions in this plane the velocities are as the radii of the ellipse on OA and OB.

In all directions in this plane there are rays vibrating at right angles to the plane, because they all possess a normal to the ellipsoid at Z. They travel with like velocities, $OC = \frac{1}{OZ} = \frac{1}{\gamma}$. The wave front is a circle wholly within the elliptical wave front.

In the plane $ZXZ'X'$ for all points R on the surface of the ellipsoid there are rays vibrating in the plane $ZXZ'X'$, yielding an elliptical wave front whose major and minor axes are, Fig. 69: in the direction OZ, $OA = \frac{1}{OX} = \frac{1}{\alpha}$, and in the direction OX, $OC = \frac{1}{OZ} = \frac{1}{\gamma}$. In all directions in this plane there are rays vibrating at right angles to the plane in the direction of the normal to the ellipsoid OY. The velocity of these rays is $OB = \frac{1}{OY} = \frac{1}{\beta}$. The wave front is a circle which intersects the elliptical wave front at four points, D, D, D', D'. Along the line OD or OD' the two rays vibrating at right angles to one another travel with the same velocities. In these directions light behaves somewhat as it does parallel to the optic axis in uniaxial crystals. For this reason these directions, OD, OD', are called optic axes. As compared with the primary optic axes noted in connection with the indicatrix, they are *secondary* optic axes.

Further discussion of the behavior of light passing through a biaxial crystal is complicated by reason of the fact that for points R, outside the three planes of symmetry the normals Rn will not lie in the plane of section, but be inclined to it. The completed wave surfaces are warped surfaces symmetrical to the three planes of symmetry through the axes X, Y, Z, whose cross sections in these planes have been described. The external surface has four circular conical depressions at the points D, D, D', D'. About each one of these depressions there is a circle at which a plane, t, is tangent to the warped wave surface. This circular ring of tangency may be developed by a consideration of the circular sections in the triaxial indicatrix.

The discussion of the case may be prefaced by the general statement that for a plate of biaxial crystal cut at any angle to the crystallo-

graphic axes the direction of vibration and the direction of transmission of the two components, derived from an incident ray entering at right angles to the plate, may be found by noting the elliptical section cut by the plate from the triaxial ellipsoid, indicatrix. The major and minor diameters of such an elliptical section are the traces of the planes of vibration of the two component rays, and the extremities of these diameters are the conjugate points, R, R', on the surface of the ellipsoid, from which normals to the surface determine the directions of transmission of the rays, their directions of vibration, and their velocities.

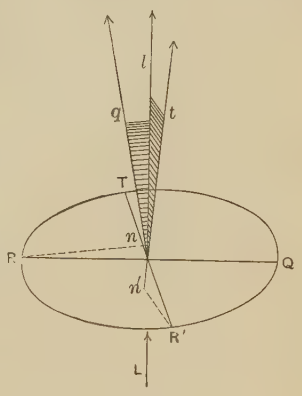

FIG. 70.

If the plate is not cut parallel to one of the planes of symmetry through XYZ, the normals Rn, $R'n'$, to the surface of the ellipsoid at the extremities of the major and minor diameters of the elliptical section, Fig. 70, will not lie in the plane of the plate but will be inclined to it. Therefore, the directions of both of the rays, q, t, at right angles to these normals will not be perpendicular to the plate. Both rays will be refracted for normal incidence of the light, Ll. Both are extraordinary rays. That is, in biaxial crystals both components of an incident ray behave in general as extraordinary rays.

The relation between the directions of vibration of the two components just mentioned and the position of the optic axes may be pointed out in this connection, though its application is made in the discussion of the interference figure in converging light (p. 173). The section cut from the triaxial ellipsoid by the plane normal to the incident ray—the ray front—is an ellipse whose major and minor diameters are the traces of the planes of vibration of the resulting components after the light passes the center point of the ellipsoid. Now this plane of the ray front intersects the planes of circular sections in the ellipsoid, the traces of which intersections must be diameters of the elliptical section having equal lengths, since each trace is the diameter of equal circular sections. The angles between these equal diameters of the ellipse must be bisected by the major and minor diameters of the elliptical section—the traces of the planes of vibration under discussion. Further, a plane passing through the incident ray and one of the optic axes of the biaxial crystal is perpendicular to the circular

section normal to that optic axis, consequently the trace of this plane in the plane of the ray front must be at right angles to the trace in it of the circular section which is normal to this optic axis. The same is true of the trace of a plane through the incident ray and the other optic axis, so that the angles between the traces of these last-mentioned planes in the plane of the ray front must be bisected by the traces of the planes of vibration of the components of the incident ray. It is possible then to find the directions of vibration of the components of an incident ray by bisecting the traces in the plane of the ray front made by planes containing the ray and the optic axes.

In the special case, in which the plate is cut parallel to one of the circular sections in the indicatrix, light entering at normal incidence could vibrate in any azimuth, since the section of the indicatrix is circular and all diameters are alike (Fig. 71). But for successive posi-

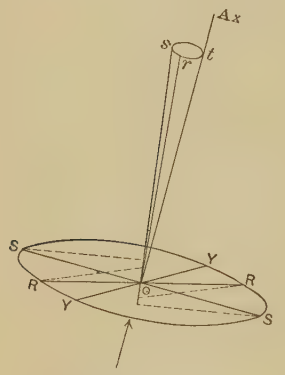

Fig. 71.

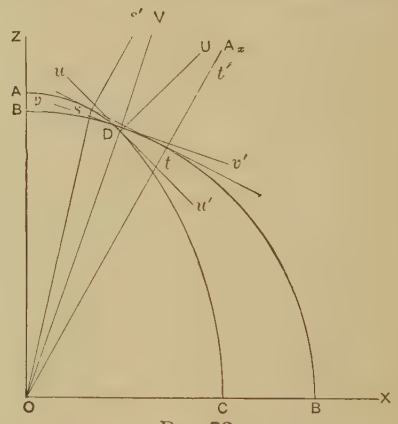

Fig. 72.

tions of R on the surface of the ellipsoid the normals, Rn, would not lie in the plane of the circular section except when R is at the extremity of the axis Y, that is, in a plane of symmetry. When the ray vibrates along OY it travels in the direction of the primary optic axis, A_x, with a velocity $OB = \frac{1}{OY} = \frac{1}{\beta}$. It reaches the wave front at t, Fig. 72. The ray front is tangent to the circular section of the wave front at this point, t, and the ray would leave the crystal plate at right angles, tt'. For any other position of R the normal Rn would be inclined to the plane of the circular section, Fig. 71, the ray passing through the center at right angles to it would be inclined to the plate and would travel with a velocity $= \frac{1}{Rn} > \frac{1}{\beta}$, because Rn is less than the radius of the circle,

$OY=\beta$, the hypothenuse of the right-angle triangle made by Rn, the ray, and the radius of the circular section. The refracted ray would leave the plate in a direction parallel to the incident ray. It follows from this that for all directions of vibration of light entering normal to the circular section there will be within the crystal a hollow cone of rays traveling with different velocities, which will leave it in a direction parallel to the direction of incidence, the direction of the optic axis. Therefore the ray fronts for each element of the hollow cone are in one plane, ts, Fig. 72, perpendicular to the hollow cylinder of emerging rays, ss', tt'. This plane must be tangent to the wave surface in a circle passing through the point t already noted (Fig. 69).

The phenomenon just described is called internal conical refraction, and takes place when light travels through a biaxial crystal parallel to an optic axis. The size of the angle of the cone depends on the inclination of the circular section to the axes X and Z and the relative values of α, β, γ. It is larger the larger the angle between the optic axes and the greater the difference, $\gamma-\alpha$. It is seldom more than 2°.

Considering the behavior of light traveling along the secondary optic axes, OD, Fig. 72, the outer wave surface passes from the circular ring of tangency to the point D, where the elliptical and circular sections of the wave surfaces intersect, forming a funnel-like depression. At this point there are innumerable tangents vv', uu', etc., to the wave surface, each representing a ray front for a ray traveling along OD. There are, therefore, innumerable rays possible along OD, traveling with like velocities but vibrating in different planes. Upon leaving the surface of a crystal plate they would advance in directions normal to the inclined ray fronts, and would constitute the elements of a hollow cone, VDV'. This is the phenomenon of external conical refraction, the angle of which is also exceedingly small.

It is to be noted that the directions of the secondary optic axes nearly coincide with those of the primary optic axes and that the behavior of the two is blended in ordinary interference phenomena.

The indices of refraction, α, β, γ, vary with the wave length of the transmitted light. Moreover, they vary at different rates, consequently the shapes of the ellipsoid are different for each kind of light, and the angle between the optic axes also varies with the color. This is called the dispersion of the optic axes, which is described on p. 181.

Interference Phenomena in Biaxial Crystals. — In Parallel, Plane-polarized Light.—When this is monochromatic the behavior of polarized light on passing through a plate of biaxial crystals

is in most positions the same as it is in uniaxial crystals. It is separated into two components, vibrating in planes at right angles to one another, traveling with different velocities, and emerging in different phases. As already noted, however, in most positions of the crystal plate with normal incidence, both components are refracted. In plates cut parallel to one of the three planes of symmetry in the indicatrix both rays are transmitted without refraction for normal incidence. In plates cut at right angles to one plane of symmetry in the indicatrix and inclined to the other two, one ray is refracted in the plane of symmetry which is at right angles to the plate, while the other is not refracted for normal incidence.

According to the phasal difference between the two components on leaving the plate, when the nicols are crossed, with monochromatic light there is darkness for a phasal difference of a whole number of wave lengths, and a maximum of light for phasal differences of any number of half wave lengths when the planes of vibration of the component rays are in the 45° position with respect to the planes of vibration in the nicols. In white light the interference colors are the same as in uniaxial crystals. Upon rotating a plate between crossed nicols the light is extinguished when the planes of vibration of the component rays are parallel to the planes of vibration in the nicols. There are positions in certain biaxial crystals where this is not strictly true, owing to the dispersion of the planes of vibration for light of different colors, but in practice this variation is generally imperceptible.

When the crystal plate is cut perpendicular to an optic axis, if the plane-polarized light consists of parallel rays, with normal incidence each ray would be transmitted vibrating in the same plane as it vibrated in before entering the crystal, because the circular section of the indicatrix shows that the plane of vibration with which it enters is a possible plane of vibration within the crystal. The ray may be refracted, but its plane of vibration remains as before. Upon emerging from the crystal it would be cut off by the upper nicol, and the plate would remain dark between crossed nicols for a complete rotation.

Plane-polarized rays passing along the secondary optic axis, however, are refracted upon leaving the surface of the crystal though their plane of vibration is not shifted. Upon entering the upper nicol they no longer meet the balsam film at the angle of total reflection, and part of the light passes through the analyzer. This is true for all positions of rotation of the crystal plate. Consequently, when a biaxial crystal plate, cut perpendicular to an optic axis, is observed

between crossed nicols, it is illuminated by a constant amount of light during a rotation about the axis. The strength of the illumination depends on the angle of the cone, and this on the double refraction of the crystal.

Interference Figures in Convergent Polarized Light.—It is to be expected that the interference figures in convergent light exhibited by plates of biaxial crystals between crossed nicols will be analogous to those of uniaxial crystals. If the plate is cut perpendicular to the acute bisectrix, which in this case may be Z, and illuminated by monochromatic light, the result may be represented by Fig. 73. The lower part of the figure represents a vertical section of the crystal plate in the plane ZX, the optic axes being A, A'. The

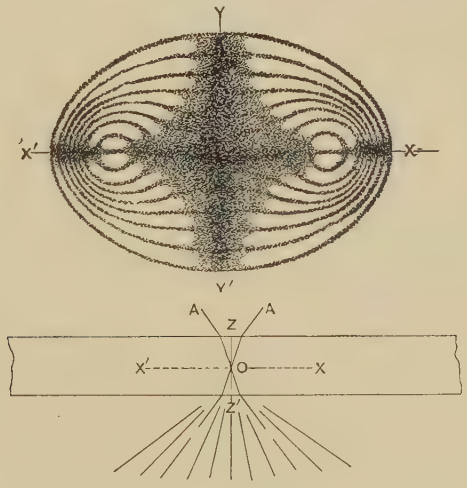

Fig. 73.

upper part of the figure represents the interference figure. XX' is the direction of the obtuse bisectrix, and YY' that of the intermediate axis. In Fig. 74 the point O is the center of the converging cone of light, and also the location of the acute bisectrix Z. The points A and A' are where the rays traveling parallel to the direction of the optic axes pass through the interference figure. They are the loci of the optic axes in the interference figure.

The directions of vibration of any pair of rays emerging from the plate at r (Fig. 74) may be found by bisecting the angles between the two lines connecting the point r with the loci of the optic axes. The bisecting lines m and n are the traces of the planes in which the vibrations take place.

When the directions OY and OX are parallel to the directions of vibration, PP' and AA', in the crossed nicols (Fig. 75), all rays emerging along the lines OY and OX will vibrate parallel to PP' and be cut out by the upper nicol. There will be two dark bands parallel to

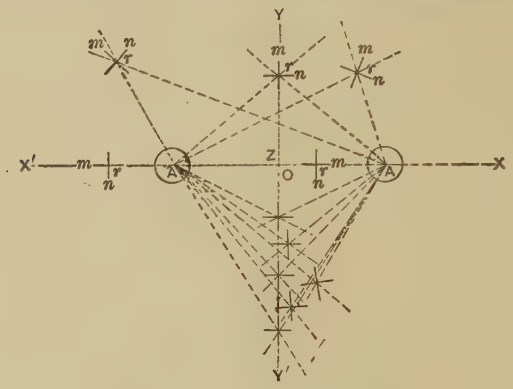

Fig. 74.

these lines: a narrow one connecting the optic axes, a broad one at right angles to this. Since rays traveling in the direction of the optic axes will emerge in the same phase, there will be darkness at

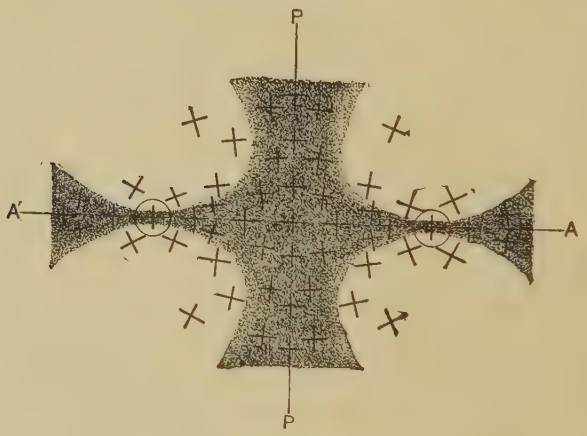

Fig. 75.

these points, which will lie on the line XX'. As the rays diverge from each of these directions the phasal difference between two component rays will increase, so that there will be rings of light and darkness surrounding each optic axis, as for uniaxial crystals. These will not

be circles, except in the immediate neighborhood of each axis. Their shapes vary as shown in Fig. 73, the curves being called lemniscates. With white light these curves are bands of color like the circles in a uniaxial interference figure. The bands parallel to XX' and YY' remain dark.

The distance apart of the lemniscates varies with the thickness of the plate and the double refraction of the crystal. It also depends on

FIG. 76.

the convergence of the system of lenses by which the interference figure is produced.

When the crystal plate is rotated, as in Fig. 76, the directions of XX' and YY' change, the optic axes revolve with the line XX', and the lemniscates with them. The dark crossed bands separate in the middle and become hyperbolas, which shift and change shape as the plate is rotated. In all positions each passes through an optic axis. In the 45° position of the crystal plate the poles of the hyperbolas are the optic axes. As the plate is further rotated they approach one

another, and meet to form crossed bands when XX' and YY' are parallel to the directions of vibration in the nicols. Upon the rotation of the plate they pass through all points in which the directions of vibration of the rays are parallel to the planes of vibration in the nicols.

It is to be noted that when the plane of the optic axes XZX' is in the 45° position, the convex side of the hyperbolas is turned toward the acute bisectrix. Also, when the plate is rotated from the position in which the lines XX', YY' are parallel to PP', AA', the hyperbolas pass into those quadrants between PP' and AA' in which the optic axes pass. This observation will serve to locate the plane of the optic axes when the axes emerge outside the field.

If the crystal plate is cut at an inclination to the acute bisectrix, the interference figure is eccentric to the center of the field of view, but its general appearance and behavior are the same as in the case described.

If the plate is perpendicular to one of the optic axes, the colored rings are concentric with the field of view and they are crossed by a dark bar which rotates about the optic axis, bending into a hyperbola as the plate is rotated. From what has already been said, it is to be noted that when the plane of the optic axes is in the 45° position with respect to the planes of vibration of the nicols, the hyperbola will be convex toward the acute bisectrix and concave toward the obtuse bisectrix. When, however, the angle between the optic axes is 90°, the hyperbola will be equally curved toward both axes, that is, it will be a straight line. It will not curve when the plate is rotated. This behavior of the hyperbola in a section cut perpendicular to the optic axis is an indication that the angle between the optic axes is nearly 90°. A good illustration of this case is to be found in olivine.

If the plate is cut perpendicular to the obtuse bisectrix, the interference figure is like that furnished by a section perpendicular to the acute bisectrix, except that the loci of the optic axes are farther apart. To determine whether the bisectrix perpendicular to a plate of biaxial crystal is the acute or obtuse one, it is necessary to determine approximately, at least, the value of the angle between the optic axes. In the microscopical study of mineral sections, when it is not possible to rotate the plate about the axis perpendicular to the plane of the optic axes, the value of the angle between the optic axes may be estimated in terms of the diameter of the field of view when the angular aperture of the objective lens is known, and when the index of refraction of the mineral is also known. For the angle actually observed is the angle in air, expressed by $2E$.

The relation between $2E$ and $2V$, the angle between the optic axes, is shown in Fig. 77, in which E corresponds to the angle of incidence and V to the angle of refraction of a ray passing along an optic axis. $n=\frac{\sin i}{\sin r}=\frac{\sin E}{\sin V}$ and $\sin E=n \sin V$, in which $n=\beta$, the index of refraction of light traveling in the direction of an optic axis. From this we may calculate the size of the optic axial angle for various values of n which will just equal the aperture of a particular lens. In such a case the loci of the optic axes fall on the circumference of the field of view.

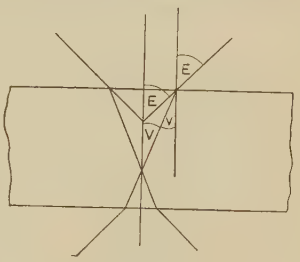

FIG. 77.

Owing to the rather high refraction of many biaxial minerals occurring in rocks, the loci of the optic axes may fall just outside the field of view when the axial angle is large. In such cases the acute or obtuse character of the bisectrix is indeterminable from the interference figure.

Exact determinations of the angle between the optic axes can only be made on sections of crystals that can be rotated in the plane of the optic axes, and such determinations are not possible on the ordinary rock section. Approximate determinations may be made in favorable

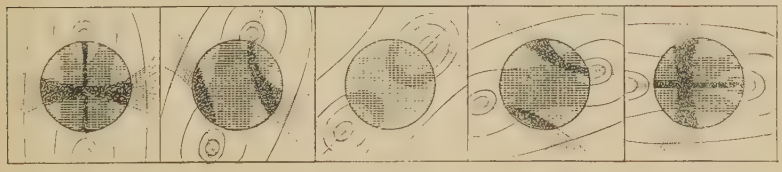

FIG. 78.

cases by measuring with a micrometer scale the apparent distance between the poles of the hyperbolas in biaxial interference figures, and calculating from this and the known angular apperture of the lens the angle between the optic axes. For descriptions of the various methods the student is referred to Rosenbusch-Wülfing's Mikroskopische Physiographie der Mineralien und Gesteine, Vol. I, Part I, p. 323 et seq.

When the optic axes lie outside the field of view, as in Fig. 78,[1] the visible part of the interference figure is the central portion only, composed of broad, colored lemniscates, across which the hyperbolas open

[1] Figs. 78, 79, and 80 are after Lévy and Lacroix.

and close when the plate is rotated. The obtuse angle may be so large as to approach 180°; when this is reached the crystal is uniaxial. It follows from this that a uniaxial crystal cut parallel to the optic

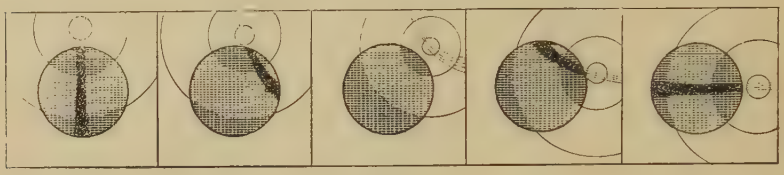

Fig. 79.

axis yields an interference figure which is like that of a biaxial crystal cut perpendicular to an obtuse bisectrix.

When the mineral plate is not perpendicular to the acute bisectrix, but is inclined to it, the normal to the plate lying between the bisectrix and one of the optic axes, but one dark hyperbola crosses the field during a rotation of the plate between crossed nicols, as shown in Fig. 79. And when the mineral plate is at right angles to one of the optic axes, the dark hyperbola appears as a bar passing through the center of the field, bending and changing its position as the mineral plate is rotated (Fig. 80). The bar is straight when the plane of the optic axes is parallel to one of the principal planes in the nicols. When it is curved, it is convex toward the acute bisectrix. It follows from this that when the angle between the optic axis is 90°, and the bisectrices are of equal value, the bar curves equally toward both, that is, it remains straight upon rotation of the plate. The curvature of the

Fig. 80.

bar then is an index of the size of the angle between the optic axes. The curvature is greater the smaller the angle $2V$.

Determination of the Optical Character of Biaxial Crystals.— When the location of the acute and obtuse bisectrices in a plate of a biaxial crystal is known, it is possible to determine the positive or negative character of the crystal by noting which is the direction of vibration of the fast and which that of the slow ray. This may be done by using a mica plate or a quartz wedge, or a selenite plate. In

Fig. 81 if the plate is cut perpendicular to the acute bisectrix and the loci of the two optic axes appear within the field of view, the obtuse bisectrix is in the plane of the optic axes, and the intermediate axis, Y, is normal to it.

When a mica plate is used to determine the optical character, the crystal is oriented so that the plane of the optic axes is parallel to one of the planes of vibration in the nicols. The mica plate, M, is placed in the 45° position, the direction of the arrow passing diagonally through two opposite quadrants of the interference figure. Then, by analogy with uniaxial crystals, if the mineral is optically positive, the colored lemniscates will expand from the loci of the optic axes in the quadrants lying across the direction of the arrow, and they will con-

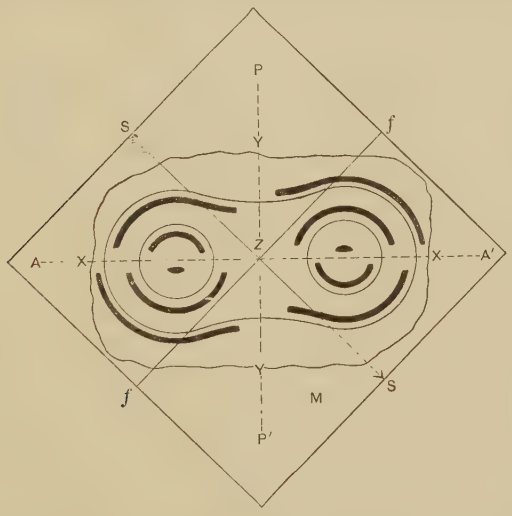

Fig. 81.

tract in the quadrants lying along the direction of the arrow. It seldom happens, however, that this test can be applied satisfactorily in the case of extremely thin sections. It is better to use the quartz wedge, inserting the thin end first, and noting the movement of the colored lemniscates. In this case the biaxial plate should be placed so that the plane of the optic axes lies in the 45° position. If the quartz wedge is placed over the biaxial plate, so that the directions of vibration of the slow rays in each mineral are parallel, the effect is as though the crystal plate were thickened—the lemniscates contract toward the optic axes. If the wedge is placed in the opposite direction, so that the fast ray in one mineral vibrates parallel to the vibrations of the slow ray in the other mineral, the effect is as

though the crystal plate were thinned; the lemniscates expand from the optic axes. Caution must be used in this case to note whether the total double refraction of the crystal plate is compensated by the quartz wedge, which will be shown by the darkening of one of the lemniscates which moves away from the optic axes. When this has passed, the further advance of the wedge has the effect of thickening the plate, and the lemniscates move toward the optic axes.

Other methods of determining whether the obtuse or acute bisectrix is the direction of the fast or slow ray depend on the interference figure for determining the location and identification of the bisectrices and afterwards using the interference color of the plate in parallel polarized light as a means of determining the fast and slow rays by the quartz wedge or selenite plate in the manner already described for uniaxial crystals (p. 145).

If the plate is cut perpendicular to one optic axis it is possible to determine the optical character of the crystal by rotating the plate until the plane of the optic axes is 45° to the planes of vibration in the nicols, noting that the hyperbola is convex toward the acute bisectrix, and placing over it a mica plate. If the hyperbola moves toward the acute bisectrix the crystal is positive, if it moves toward the obtuse bisectrix the crystal is negative. This is demonstrated by the diagram Fig. 82. O is the locus of an optic axis, ZX is the plane of the optic axes, and Y is the optic normal. If OZ is the acute bisectrix, and the direction of vibration of the slow ray (optically positive crystal), then OX is the direction of vibration of the fast ray. Light traveling along the optic axis has a velocity $=\frac{1}{\beta}$; consequently any ray emerging between the optic axis and the acute bisectrix, OZ, as at a, is faster than this, $>\frac{1}{\beta}$, and any ray emerging between the optic axis and the obtuse bisectrix, OX, as at b, is slower than this, $<\frac{1}{\beta}$. When the mica plate is placed so that the direction of

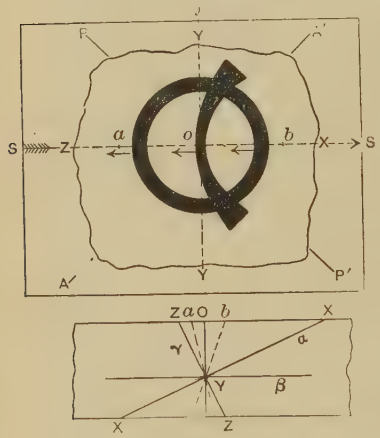

Fig. 82.

vibration of the slow ray in it, the arrow, is parallel to the plane of the optic axes in the biaxial crystal, then between the optic axis and the acute bisectrix the faster ray in the plate vibrates parallel to the slow ray in the mica, and the effect is a thinning, lemniscates move from the optic axis. and this moves toward the acute bisectrix. Between the optic axis and the obtuse bisectrix the reverse condition obtains, slow ray vibrates parallel to slow ray, the effect is a thickening, the lemniscates move toward the optic axis, that is, also toward the acute bisectrix. If the mineral were optically negative, the lemniscates and hyperbola would move in the opposite direction, away from the acute bisectrix.

Dispersion.—It has already been stated that the values of the principal indices of refraction, α, β, γ, vary with the wave length of the light transmitted, consequently the form of the triaxial ellipsoid—indicatrix—changes with each kind of light, and with this change of form there must be a corresponding change in the position of the optic axes. The angle between the optic axes in any crystal is different for each kind of light. The optic axes are dispersed. Whether the axes are further apart for red light than for violet depends upon the relative values of α, β, γ for these colors, and this is characteristic of different minerals. The fact is expressed by $\rho > v$ or $\rho < v$, and it may be observed in the interference figure for white light by noting the color of the edges of the hyperbolas when the plane of the optic axes lies in the 45° position. The hyperbola consists of superimposed hyperbolas for all the components of white light. If there were no dispersion of the optic axes these hyperbolas would coincide along their center, but as the axes are dispersed the hyperbolas are shifted over one another. The one farthest from the acute bisectrix corresponds to the color with the largest optic angle. If this were red then red would be cut out of white light and the resultant color would be bluish. In this case the hyperbola nearest the acute bisectrix would be that for blue light, which would be cut out letting red dominate. So that when the axes for red are more dispersed than those for blue, $\rho > v$, the edge of the hyperbola farthest from the acute bisectrix—the concave side—is *blue*, that nearest the acute bisectrix—the convex side—is *red*. The color appears as a thin fringe to the black hyperbola.

Not only does the form of the ellipsoid change with light of different wave lengths but the positions of the principal axes of the ellipsoids may change, according to the crystallographic symmetry of the mineral. There are three cases possible:

1. *The three planes of symmetry in the ellipsoids coincide for light of all wave lengths.* That is, the three principal axes, X, Y, Z, of all the ellipsoids lie in the same three directions in the crystal for all colors. But it does not follow that for all colors the same axes, major, intermediate, or minor, are in the same directions. In some cases two interchange places for different colors.

Crystals of this kind belong to the orthorhombic system, and the three principal axes of the ellipsoid coincide with the three crystal axes, a, b, c, for all colors. Any one of the axes a, b, c may be parallel to the major, intermediate, or minor axis of the ellipsoids, according to the particular mineral.

In these minerals the dispersion of the optic axes is symmetrical to two planes of symmetry intersecting in the acute bisectrix, as in Fig. 83, in which $\rho > v$, the colored lemniscates are dispersed together

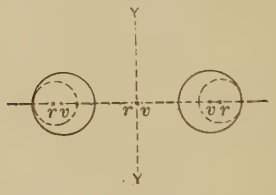

FIG. 83.

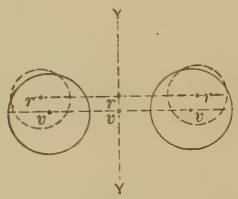

FIG. 84.

with the axes, and the variations in color are alike on both sides of the plane of the optic axes and on both sides of a plane through the bisectrix at right angles to this plane.

In brookite the Z axis is the acute bisectrix and is parallel to the crystal axis a, and the plane of the optic axis for red and yellow is parallel to the third pinacoid (001), $2E\rho = 55°$; but the plane of the optic axes for green is parallel to the second pinacoid (010), $2E\gamma = 33°$. Consequently for some intermediate color brookite is uniaxial.

2. *The ellipsoids for all colors have one plane of symmetry in common, and one of the principal axes perpendicular to this plane.* The other principal axes are dispersed in the common plane of symmetry. Either axis, X, Y, or Z, may have a constant position for all colors.

Crystals of this kind belong to the monoclinic system. The common plane of symmetry for all colors coincides with the second pinacoid (010), the plane of symmetry for most crystals in this system, and the common axis for all colors coincides with the crystal axis, b.

In these minerals the dispersion of the optic axes depends upon whether the common axis is the acute or obtuse bisectrix, or the optic normal.

(*a*) *If the common axis is the obtuse bisectrix*, the plane of the optic axes is at right angles to the plane of symmetry. The acute bisectrix is dispersed in the plane of symmetry. When the angle between optic axes for red is greater than that for violet, $\rho > v$, the result is illustrated in Fig. 84. The colors in the lemniscates are similarly disposed about both optic axes and are distributed symmetrically on both sides of the plane of symmetry, which is perpendicular to the plane of the optic axes. This is called *horizontal dispersion.*

(*b*) *If the common axis is Y*, the normal to the plane of the optic axes, this plane lies in the plane of symmetry. The acute bisectrices are dispersed, and the result is illustrated in Fig. 85 when $\rho > v$. The colors of the lemniscates are unlike about the optic axis, and are distributed symmetrically with respect to the plane passing through the optic axes. This is *inclined dispersion.*

(*c*) *If the common axis is the acute bisectrix*, the planes of the optic axes are dispersed, and when $\rho > v$ the result is illustrated in Fig. 86.

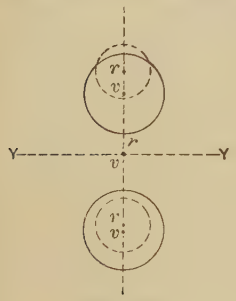

Fig. 85.

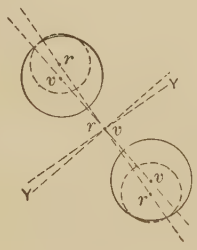

Fig. 86.

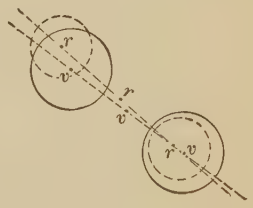

Fig. 87.

The colors of the lemniscates are alike about both optic axes, but are symmetrical across a point only. This is called *crossed dispersion.*

3. *The ellipsoids for all colors have no planes or axes in common.* The principal axes and planes of the optic axes are dispersed in an unsymmetrical manner (Fig. 87).

The distribution of color in the lemniscates about each optic axis is different, and is not symmetrical to a line or a point. Crystals of this kind belong to the triclinic system.

Abnormal Interference Colors in Biaxial Crystals.—In addition to those abnormal interference colors due to the absorption of light of particular wave lengths by a crystal, which give it a definite color, there are others which are brought about by the dispersion of the optic axes when the angle between them is so small that for light of a particular color it is zero, or nearly so. In such a case, as in zoisite, in a

section cut at right angles to the acute bisectrix the light for which the optic axial angle is zero is cut off between crossed nicols, as though the crystal were uniaxial for this color. The resulting interference color is strongest in those parts of the spectrum for which the optic axes are farthest apart. In zoisite the optic angle is nearly zero for the red end of the spectrum, and the interference color in sections normal to the acute bisectrix is indigo and blue. The same is the case with penninite.

Sections of crystals exhibiting marked dispersion of the bisectrices for different kinds of light will not become dark in any position between crossed nicols when illuminated by white light, but show modifications of the dominant interference color as they approach the position in which the bisectrices are successively parallel to the principal optic sections of the nicols.

Changes in the Optical Behavior of Crystals due to Molecular Strain.—A condition of homogeneous molecular strain may be produced in a crystal, or in a homogeneous amorphous body like glass, by a uniform change of temperature or by a pressure exerted uniformly on all sides of it, as in the case of hydrostatic pressure or of gas pressure. Within certain limits the effect is to move the molecules farther apart or closer together without changing their arrangement, producing a change of volume and of density. Beyond these limits the changing of the molecular arrangement is equivalent to the transformation of the crystal into one of another kind. Such transformations are not considered in this connection.

In general, and in the case of rock minerals and glass, changes of temperature and pressure affect these substances in the opposite manner. That is, increase of temperature usually increases the volume, and increase of pressure decreases it. Some of the effects on the optical properties of glass and crystals may be stated briefly as follows:

Isotropic media, amorphous glass, and crystals in the isometric system remain isotropic upon a change of temperature. But with a change in density there is a change in the index of refraction of each substance, so that with increase of temperature there is a decrease in the value of the index of refraction.

Uniaxial crystals remain uniaxial upon change of temperature, but the changes in the refraction, and consequently in the double refraction, do not bear a constant ratio to the amount of change in temperature. That is, the rate of change in the refraction of the ordinary ray may be different from that of the extraordinary ray. In fact they vary in opposite directions in certain minerals. Thus in quartz Fizeau

found that both ω and ε decrease with increase of temperature, and at nearly the same rate. In beryl the refractive indices, ω and ε, increase with increase of temperature, as observed by Dufet and Offret; the increase for ω being greater than that for ε. In calcite Fizeau found that both indices, ω and ε, increase with rising temperature; that for ε being noticeably greater than that for ω. From this it is seen that the double refraction is increased in some minerals and decreased in others by a rise of temperature.

In *biaxial* crystals the three principal indices of refraction are affected differently by a change of temperature, each at its own rate, so that the shape of the triaxial ellipsoid, or indicatrix, for each color or value of λ changes. This not only modifies the double refraction, but more noticeably the angle between the optic axes. Offret found that the double refraction for different pairs of the principal indices in one substance in some cases increased, in others decreased, with increase of temperature, but that, in the minerals investigated, the dispersion increased. Des Cloizeaux investigated the changes in the optical angle of various crystals and found that the change of angle in some minerals is very slight, while in others it is very marked. Of these, gypsum and orthoclase (sanidine) are good examples. With increase of temperature the axial angle decreases, so that it is zero for particular values of λ at temperatures less than 100° in the case of gypsum, which under such conditions is uniaxial for a particular color. Above this temperature the plane of the optic axes is at right angles to its former position, and with still further rise in temperature the optic axial angle increases in value.

Stress acting in one direction instead of in all directions may produce homogeneous strain, the effect of which on the optical properties of glass and crystals is in general as follows:

Isotropic media become double refracting. Amorphous substances like glass, when subjected to compression, behave as though denser in the directions of the pressure than at right angles to it. Consequently light, in passing through such a strained substance at right angles to the line of pressure, is separated into two components, one vibrating in the direction of the line of pressure and having a lower index of refraction than the other component which vibrates at right angles to it. It is as though a sphere representing the index surface of the isotropic medium were changed by compression into an oblate ellipsoid of rotation whose axis is in the direction of pressure—the indicatrix of an optically negative uniaxial crystal. Tension in one direction produces the opposite effect. Glass under tensile stress

would have the properties of an optically positive uniaxial crystal. The sphere would be elongated to a prolate ellipsoid of rotation. Stresses in more than one direction would produce the optical effect of a biaxial crystal.

Isotropic crystals, or those in the isometric system, become biaxial when stressed in any one direction, except in the line of the three axes of symmetry that are perpendicular to one another, that is, the three crystallographic axes; and also when in the line of the four threefold axes of symmetry, that is, the axes connecting opposite corners of a cube.

Uniaxial crystals when stressed in the direction of the optic axes remain uniaxial, but have their double refraction increased or decreased according as they are optically positive or negative and are subjected to tension or compression. The particular effect in each case may be understood by considering the optical indicatrix, a prolate ellipsoid of rotation for positive crystals and an oblate ellipsoid of rotation for negative ones, compressed in the direction of the axis of rotation under pressure, or elongated in this direction under tension. The change which further accentuates the form of the indicatrix increases the double refraction; that which causes the indicatrix to approach nearer to the form of a sphere diminishes the double refraction.

When stressed in other directions, uniaxial crystals become biaxial, that is, the indicatrix becomes triaxial. When a positive uniaxial crystal is compressed at right angles to the optic axis, this axis becomes the acute bisectrix and the plane of the optic axes lies in the direction of the line of pressure, as though the uniaxial indicatrix were compressed to a triaxial one whose major axis coincided with the original optic axis, and whose minor axis was in the line of pressure. Conversely, when a negative uniaxial crystal is compressed in a similar manner, the original optic axis becomes the acute bisectrix and the plane of the optic axes lies at right angles to the line of pressure. A tensile stress operates in an opposite manner. It is interesting to note that a uniaxial crystal exhibiting rotary polarization in the direction of the optic axis, such as quartz, when rendered biaxial by lateral pressure, exhibits rotary polarization in the direction of each of the optic axes, the polarization being elliptical instead of circular

Biaxial crystals stressed in the direction of one of the three principal axes of vibration, that is, along one of the principal axes of the indicatrix, are affected in such a manner that the shape of the ellipsoid is changed, but not its orientation in the crystal. The indices of

refraction and the angle between the optic axes are changed. In general it may be stated that the refraction of the light which vibrates in the direction of the compression is decreased. From this the effect of applying a pressure in the direction of any one of the three axes of the indicatrix in an optically positive crystal, or in an optically negative crystal, may be deduced. It is as though the triaxial ellipsiod were compressed in the direction of the stress, with the consequent change of shape and its effect on the angle between the optic axes. If the direction of stress is not parallel to one of the principal axes of the indicatrix, not only its shape, but the orientation of its principal axes, are changed. For a fuller discussion of this subject the student is referred to Groth's Physikalische Krystallographie.[1]

When the strain in a crystal or amorphous glass passes the limit of elasticity, and there is a permanent displacement or set, the corresponding modification of the optical properties becomes permanent. The most familiar example of this is the irregular optical orientation in some quartz crystals, which shows itself in undulatory extinction between crossed nicols. Permanent strain in rock glasses is often indicated by weak double refraction.

The Color of Minerals.—According to the kind and amount of absorption experienced by light in passing through crystals, they are variously colored in transmitted light. Their color in incident light is also due to the kinds of color absorbed and the kinds reflected.

Those crystals in which there is no appreciable absorption transmit all parts of white light and are colorless. If they absorb any part of white light, the transmitted light is colored. The possible variations in color depend upon a number of factors, such as the composition of the mineral, the presence of inclusions, visible or invisible, and the optical nature of the crystal.

Isotropic homogeneous minerals, if colored, exhibit the same color in all directions of transmission for equal thickness of substance.

Uniaxial crystals, if colored, may exhibit different degrees and different kinds of absorption in different directions through the crystal, or there may be no difference. When there is a difference, the absorption may be a maximum for light vibrating parallel to the optic axes. It will then be a minimum for light vibrating perpendicular to the axis, and the variation in absorption will vary as the radii of an ellipse whose major and minor axes correspond to the maximum and minimum absorptions just mentioned. The absorption surface for

[1] 3d Edition, p. 183 and p. 209 et seq.

each kind of light, expressing the variations in all directions in the crystal, would be an ellipsoid of rotation, whose axis is the optic axis of the crystal. But the form of this surface bears no other fixed relation to the ellipsoid of refraction. One may be a prolate ellipsoid, the other may be prolate or oblate. That is, the rays which are fastest may be the most absorbed or the least absorbed The variation may be from colorless to a strong color, or from one color to another color, or from a light to a dark shade of the same color.

Biaxial crystals, if colored, may exhibit no difference of color in different directions, or a notable difference. In general it may be said that the surface which would express the variations in absorption of each kind of light in all directions is that of a triaxial ellipsoid analogous to that for refraction. But this is not strictly true for crystals of the triclinic system.

It follows from this that biaxial crystals may show three colors, or tints of colors, according to the direction of transmission of the light. The directions of maximum, minimum, and intermediate absorption correspond to the principal axes of the triaxial ellipsoid of refraction when these coincide for all kinds of light, that is, for orthorhombic crystals and for those in monoclinic crystals parallel to the crystallographic *b* axis. But when these axes are dispersed, as in triaxial crystals, and in the plane normal to the *b* axis in monoclinic crystals, the directions of principal absorption may not coincide strictly with the axes of the ellipsoids. In some cases they have noticeably different directions. The exhibition of different colors in different directions is called *pleochroism.* It is customary to describe the pleochroism by naming the color of the light transmitted through a crystal vibrating parallel to the three principal axes of the ellipsoid, that is, the fastest, intermediate, and slowest rays. Using the letters employed in the diagrams these are *X*, direction of vibration of the fastest; *Y*, of the intermediate; *Z*, of the slowest. These correspond to **a**, **b**, **c**, in most writings. But, as already noted, these letters are easily confused with the crystallographic axes, *a*, *b*, *c*; it is therefore better to employ *X*, *Y*, *Z*.

Interference Phenomena due to Absorption.—When a mineral exhibiting strong absorption of light in one direction, as biotite, is overlaid by, or superimposed on, a double-refracting mineral, such as quartz, there is an interference phenomenon due to the fact that the light passing through the mica is reduced to that vibrating in only one direction, as though the mica were a colored Nicol prism. According to the position of the planes of vibration in the mica with respect

to that of the light coming from the polarizer, and also with respect to the planes of vibration in the other double-refracting minerals, the interference of the light leaving the minerals or passing through an upper nicol, analyzer, will be modified in a manner easily understood by following the discussion of interference phenomena given on p. 137.

Preparation of Thin Sections of Rocks.—Fragments of rocks that are to be made into thin sections may be either broken from the rock or sawed from it. It is usually sufficient to chip off by means of a small hammer a moderately thin, flat piece about 3 cm. or about an inch across the flat side. This should be free from cracks and as fresh and unaltered as possible, unless it is desired to study processes of alteration in the rock minerals. When it is not possible to chip off thin flakes and it is convenient to saw the rock specimen it is better to save the time necessary to grind a thick chip by sawing a thin piece from the rock. This is often necessary in order to furnish a definitely oriented section, especially one across planes of fissility or schistosity, as across a mica-schist.

Sawing may be accomplished by means of a continuous wire passing over wheels and fed with powdered carborundum or emery, the rock specimen being pushed upon a support steadily against the wire; or it may be done by a diamond saw, a thin metal disk charged with diamond dust, properly set on an axle rotated by a motor of any kind. It is necessary to keep the saw cool by means of water dropped on it or taken up by it from a pan. The sawing may also be done by a metal disk fed with powdered carborundum. With a carefully adjusted saw it is possible to cut sections so thin that much time is saved in the processes of grinding.

Grinding is necessary to prepare a plane, polished surface on one side of the rock fragment which is afterwards cemented to glass, when the remainder of the fragment is either sawed off, leaving a very thin plate adhering to the glass to be further reduced by grinding, or the fragment is ground down without sawing.

The first grinding is usually done by holding the rock fragment in the fingers, but if the fragment is quite thin it may be cemented to a thick plate of glass about 5 cm. square. The grinding may be done by hand on a flat plate of metal, or better on a rotating disk operated by a motor. At first the grinding material may be rather coarse, but when the surface of the rock fragment is reduced to a uniform plane finer material should be used, extremely fine dust being used for polishing. In changing from one operation to another it is necessary to wash the rock fragment free from the coarser material and to use

different plates. The coarser grinding may be done on the wheel, and the polishing on a flat plate by hand. Care should be taken constantly to avoid wearing the surface of the wheel and flat plate uneven, as it is necessary to produce a plane surface on the rock fragment.

When one side of the fragment is smooth and polished it is cleaned with a stiff brush in water, in order to remove all grinding material and afterwards dried carefully by heating to remove moisture that might be driven out when the fragment is placed on hot balsam. If it has been cemented to glass, it is removed by heating the glass. The polished side of the fragment is cemented to a thick plate of glass about 3 cm. square by means of Canada balsam or other similar cement.

The Canada balsam may be either viscous or solid. If viscous, it requires a slight amount of heating to drive off the more volatile constituents so it may harden upon cooling. A little experience is required to produce the proper condition, as too long heating will remove too much and render the balsam too brittle after cooling, or it may produce a yellow color. The balsam may be heated to the proper extent in considerable quantity in a porcelain dish and kept in the solid state in broken fragments, or in rods drawn out just before it hardens. It then requires but little heating when used to cement the rock fragment to glass. Canada balsam in a liquid form, prepared by dissolving the solid balsam in ether or other volatile solvent, may be used for cementing without heating when this is desirable, but it requires considerable time for the solvent to evaporate sufficiently to permit the balsam to harden.

A cement composed of 20 parts by weight of white powdered shellac and 7 of Canada balsam is sometimes used. After thorough mixing in a dish upon a water-bath it may be drawn into rods before hardening and used in a solid form.

Before cementing the rock to the glass the latter is warmed on a metal stand and a drop or fragment of balsam placed upon it. The rock fragment is heated over a lamp flame and freed from dust or other matter and placed upon the balsam with the polished face toward the glass, care being taken to avoid introducing gas bubbles between the rock surface and the glass plate, as they cause the thin section to crack off before the work is finished. In case they are present it is better to remove the rock fragment and remount it than to run the risk of losing it after the work of preparation is nearly complete.

The rock fragment should be pressed close to the glass in order to bring the polished surface as nearly parallel to the glass as possible,

so that the grinding away of the remainder of the fragment may leave a thin section of uniform thinness. The glass plate should be thick enough to prevent its bending under the pressure of the fingers holding it against the wheel or metal plate, as this will prevent the thin section from being uniformly thin, rendering it thinner either on the edges or at the center.

With a well-adjusted diamond saw it is possible to saw off the greater part of the rock fragment after it has been cemented to the glass plate, leaving a comparatively thin section of the rock to be reduced by grinding. This is an economy of time. At first the grinding is conducted with coarse abrasive, but great care must be taken to stop using the coarse material before the section becomes so thin that it is torn through by it. In the last stages of the grinding, finer and finer abrasive powder is used, the coarser grains being carefully removed by washing, and the last reduction being made on separate grinding plates by hand. It is advisable to watch the last stages of the process closely, as it is desirable in all cases to make the section as thin as possible, but the least step too far will destroy the whole preparation. For this reason it is well to observe the section from time to time with a microscope to note the thinness, covering the rock surface with a drop of water and a cover glass.

In most cases the interference colors of the feldspars or the quartz may be taken as a standard of the thinness. They should be grayish white of the first order. In case there are dark-colored minerals present, it may be desirable to reduce the thinness of the section until the darkest silicates become transparent. It often happens that the section is thinner at the margin than at the center, when the grinding away of the thin edge is a warning of the approaching limit of the operation.

If the rock section shows no signs of cracking, the final grinding may be done on the thick glass plate, and the finished section afterwards removed to a thinner glass for the final mounting. But if the rock tends to crack up when very thin, and will not permit of its being moved to another glass after it has reached its proper thinness, it is best to remove it to the thinner glass plate before it is too thin, and to finish the grinding on it. If this is done, however, care must be taken to set the rock section close and parallel to the glass plate, for the reason already given.

When the grinding is ended, and it is necessary to remove the thin section to a fresh glass plate, the section is carefully cleaned of grinding powder by means of a brush and alcohol, the surrounding

balsam is removed by a warm knife blade, and the section loosened by gradually heating the thick glass plate. The rock section is then moved over to the fresh glass, which has been previously warmed and prepared with a drop of balsam. This should be allowed to spread slowly between the rock section and the glass, so as to exclude gas bubbles. Another drop of balsam is placed on top of the rock section, and a clean, thin glass cover placed over it and allowed to settle without inclosing bubbles. A dull point is then applied to the middle of the cover glass and moved carefully toward the margin, so as to push out the excess of balsam, leaving a thin film only between the rock section and both glasses. The excluded balsam may be subsequently removed by means of a warm iron blade and alcohol.

When the last grinding has taken place on the thinner glass plate and there is danger of the rock section cracking and spreading upon the melting of the balsam, it is advisable, after properly cleaning the section in the manner already described, to cover it with a drop of balsam dissolved in ether and place over this the cover glass, allowing the balsam to harden slowly by the evaporation of the ether.

The best sized glasses for rock sections are 28×48 mm., the cover-glasses being about 26 mm. square, leaving a sufficient space at each end for labels or for writing directly upon the glass with a diamond.

Friable and porous rocks may be ground into thin sections by first filling the pores with Canada balsam after all moisture has been driven out by heating the rock fragment. The final grinding should be done on the glass plate on which the section is to be permanently mounted. It is difficult to remove all remains of the grinding material from the pores of the rock before mounting with a cover glass, so that allowance must be made for this material when the section is studied. Extremely soft material like clay may be prepared by reducing one side of a fragment to a smooth plane by means of a knife-blade, cleaning it with water to remove loose particles, drying thoroughly, and cementing the surface to a glass plate over which has been spread a thin layer of Canada balsam dissolved in ether. When the balsam has solidified the rock is broken from the glass, leaving a thin layer adhering to the balsam and furnishing a new plane surface on the rock fragment, the particles of which retain the relative positions they had in the rock itself. After cleaning the fracture surface with a strong current of water without using a brush, and drying, it is cemented to a glass plate covered with a thin layer of balsam, and, after hardening, the rock is again broken away, leaving a thin layer

of the rock adhering to the balsam; this layer may be made thinner by washing in a strong current of water.

Preparation of Small Fragments of crystals broken from a rock for optical study may be accomplished in several ways, depending on the purpose of the investigation. For some purposes it is sufficient to cover minute fragments with a drop of water and a cover glass. The outward form is more easily recognized when the surrounding medium has a distinctly different index of refraction. For some optical tests it is better to use a medium whose refraction is nearer that of the mineral. Such liquids are glycerine ($n=1.46$), almond oil ($n=1.47$) Canada balsam ($n=1.539$), cassia oil ($n=1.606$), or any of the liquids used for the determination of the refraction of crystals.[1]

When the fragments are to be mounted permanently in balsam, it is best to cover the glass plate with a thin layer of balsam and distribute the mineral fragments carefully over it, placing on them balsam and a cover glass. Otherwise the fragments are apt to crowd together and not become scattered uniformly through the balsam.

If it is necessary to prepare thin sections of small fragments of crystals, this may be done by embedding them in Canada balsam which has been placed on a thin cover glass, which is itself cemented to a thicker glass plate. The mineral fragments are pressed into the balsam by laying paper over them and pressing them down with a flat rubber surface. When the balsam has hardened a smooth surface is ground on the mineral fragments, which are afterwards thoroughly cleaned. The thin glass cover beneath the fragments is removed from the glass plate by warming the latter rapidly, and the layer of balsam with the fragments is cemented to another glass plate over which has been spread a thin film of balsam. The balsam and fragments are pressed closely to this glass plate by the rubber, so that the ground surfaces on the mineral fragments may be parallel to it. The remainder of the fragments is removed by careful grinding until sufficiently thin sections of the minerals have been prepared. These are cleaned and covered with thin glass without removing them to another glass plate.[2]

Method of Procedure in the Optical Determination of Minerals in Mounted Thin Section.—Thin sections of minerals and rocks are usually mounted on glass by means of Canada balsam, which forms a thin film above and below the section and completely surrounds it. The balsam is isotropic and has an index of refraction of approxi-

[1] Rosenbusch and Wülfing. Mikrosk. Physio., Vol. I, Pt. 1, p. 262.
[2] Stöber, F. Bull. Soc. Min. Fr 22., 1899, 61.

mately 1.539, but its refraction must vary slightly with the extent to which the volatile constituents have been driven out. When other cement than Canada balsam is used, the index of refraction will be different and the statements made for the behavior of mineral sections in Canada balsam must be modified to suit the refraction of the cementing material used.

When a section mounted in Canada balsam is illuminated by plane-polarized white light, using the lower nicol in a microscope, the first observation made relates to the color of the mineral section.

Color of Section.—The section is transparent or opaque. In transparent sections the color is due to the absorption of transmitted light. In opaque sections, where no light is transmitted, the color noted is due to reflected light incident on the upper surface of the section. The stronger the incident light the more noticeable the color of opaque sections.

Transparent sections may be colorless or colored. In the latter case the color may be uniform throughout the crystal or not. Variation in color in one crystal section in one position, with respect to the polarized light, may be due to variation in the thickness of the section or to lack of homogeneity in the distribution of a pigment not inherent in the chemical molecule of the mineral, such as color in quartz crystals; or the chemical composition of the crystal may vary as in pyroxene.

If one crystal exhibits different colors, or shades of color, when rotated on the stage of the microscope, it is pleochroic. Sections of pleochroic minerals cut in different crystallographic positions will exhibit different colors according to the position of the plate and the direction of vibration of the polarized light. The tones and shades of color and the directions of vibration of different colored components of transmitted light are to be noted.

Refraction.—The refringence of the crystal is the next property which attracts attention. It exhibits itself by the apparent smoothness or roughness of the surface of the section and by the indistinctness or distinctness of its outlines or of cracks in it. These characters produce what is known as the apparent "relief" of the section with respect to its surroundings.

The apparent smoothness or roughness of surface and the distinctness of cracks are due to the relative refringence of the mineral and the balsam. The same is true for the definition of the outline when the mineral section is in balsam. But when, as in a rock section, the mineral may be surrounded on the edges by other minerals, the

prominence of outline is due to the relative refringence of the adjacent minerals.

It is of course dependent on the direction in which the light passes through each crystal. The best illustration of these relationships is found in calcite, which, having indices of refraction lower and considerably higher than that of balsam, changes in apparent relief when a section is rotated in polarized light.

Since the appearance is similar, whether the refringence of the mineral is higher or correspondingly lower than the surrounding medium,—compare apatite and fluorite with balsam,—it is necessary to employ Becke's method for determining the relative refringence of the adjacent media. This is especially necessary when the difference between them is slight.

The observer must be cautioned against mistakes arising when the plane of contact between two adjacent media is so inclined as to reflect the transmitted light to one side, regardless of the relative refraction of the media. The phenomena can only be safely relied on when the plane of contact is vertical or nearly so. This can be determined by observing whether the line in focus in the plane remains in one position upon changing the focus from top to bottom of the section, or whether it shifts to one side or the other.

Standards of Comparative Refringence.—Owing to the importance of distinguishing the relative refringence of colorless minerals in rock sections as a means of their identification certain relationships should be noted.

In isotropic media the refringence is constant for all positions of transmission. In anisotropic crystals the refringence varies with the crystallographic position of the section, and further with the direction of vibration of the ray which passes through a given section. When the position of vibration of the light can be definitely determined, the specific index of refraction can be stated, otherwise the refraction is something intermediate between the maximum and minimum determined for the mineral. It happens, therefore, that adjacent sections of the same kind of double-refracting mineral, like quartz, if cut in different crystallographic positions, will exhibit different refringence, the refraction of one section being higher than that of another, and this relation changing when the light vibrates in different planes.

If two adjacent quartz sections are so oriented with respect to one another that the direction of vibration of the faster ray in one section is parallel to that of the slower ray in the other, then, when plane-

polarized light passes through these sections vibrating wholly in the direction just mentioned, the index of refraction in the first section will be less than that in the second. If the light vibrates at right angles to this direction the reverse will be the case, namely, the refraction in the first section will be greater than that in the second.

When two minerals are adjacent and the refringence in one is higher than it is in the other for all positions of vibration, it remains higher for all crystallographic positions of the sections or directions of vibration of the transmitted light.

It is to be noted that in sections of uniaxial crystals there is always a direction of vibration in which the light behaves as an ordinary ray and has a constant index of refraction. When the light is made to vibrate in this direction the index of refraction has a definite value and can be used as a standard of comparison.

Owing to the frequent occurrence of quartz and feldspars, also of nephelite, leucite, and sodalite, in rocks, and the difficulty of distinguishing these minerals in colorless thin sections, it is advisable to consider in detail the refringence of each with reference to several standards of comparison.

Any mineral section, when definitely determined mineralogically and crystallographically, or any other medium may be employed as a standard. There are several, however, which are more readily determinable than others: *Canada balsam*, with constant index of refraction—1.539 approximately—is adjacent to crystal sections along the margin of rock sections and in open cracks through the section. *Quartz*, being a uniaxial crystal, always furnishes one direction of vibration, that of the ordinary ray, the faster ray, with constant index of refraction, $\omega = 1.544$. The same is true of *apatite*. The ordinary ray is the slower, and the constant index of refraction is $\omega = 1.638$. For calcite it is the slower ray, and the constant refraction is $\omega = 1.658$.

The feldspars vary in refringence with the chemical composition, the more sodic being lower than balsam and quartz, the more calcic higher than quartz. The relative refringence is shown in the diagram on page 215.

The principal indices of refraction and the double refraction of the rock-making minerals are given in the tables at the end of the book. Minerals with variable chemical composition have different indices of refraction, according to the chemical composition.

Interference Phenomena.—Examining the section with the analyzer, the nicols being crossed, the interference phenomena reveal the following facts:

Isotropism.—If there is no interference color in any position of the mineral section the substance is isotropic—either amorphous or crystal in the isometric system—or the section is a uniaxial crystal cut perpendicular to the optic axis. This will appear if an interference figure is obtained with converging light.

Extremely weak double refraction may escape detection when the degrees of darkness alone are relied on. If a selenite plate—red of the first order—is placed over the section extremely slight double refraction affects the color perceptibly.

Anisotropism—When the section exhibits interference color, the color may be uniform in tint or shade throughout the section, or it may vary in different parts of the section.

If the color is uniform, the crystal is uniformly thick and is homogeneous in chemical composition, and has like crystallographic orientation throughout.

If the color varies from place to place, there are several possibilities: (*a*) the plate may vary in thickness; (*b*) the parts of the crystal may vary in crystallographic orientation—in molecular arrangement—as in molecularly strained quartz, or as in an aggregation of crystals cut in various positions, or in twinned crystals; (*c*) the crystal may vary in chemical composition, the chemically different parts having different optical properties, though they may have similar crystallographic orientation and equal thickness, as is the case in zonally formed plagioclase feldspars.

In a rock section consisting of numerous crystals the strength of the double refraction in a particular crystal section can be determined by noting the interference color and the thickness of the section. The thickness of the section is determined by observing the interference color of a known mineral like quartz in a section cut parallel to the optic axes. The thickness of quartz which will yield a particular interference color has been determined, and the thicknesses and interference colors corresponding to various strengths of double refraction are given in the colored plate at the end of the book.

The amount of double refraction which may be observed in a given mineral varies from a maximum in the plane of the optic axis or axes to a minimum of almost nothing in sections perpendicular to an optic axis of biaxial crystals, and zero in such sections of uniaxial crystals. The higher values are characteristic of a mineral and may be used as an aid to its identification.

If the section shows a constant interference color for all positions of rotation, it is cut perpendicular to an optic axis and exhibits conical

refraction. The biaxial character of the mineral is indicated, and may be established by noting the interference figure in converging light.

In sections showing interference colors, which vary in intensity upon rotating the plate, the direction of vibration of the components of transmitted light may be determined. They vibrate parallel to the cross hairs in the microscope when the section is darkest. These directions may be related by angular measurement on the table of the microscope to any line—cleavage, composition plane of twinning, or outline.

Having located the directions of vibration of the two component rays, their relative velocities may be determined by means of the quartz wedge or the selenite plate.

Interference Figure.—Finding the interference figure in convergent polarized light, the uniaxial or biaxial character of the crystal is determined.

Uniaxial.—The uniaxial figure is shown best by sections which show the least double refraction in parallel polarized light; but others, more or less inclined, yield eccentric interference figures quite as useful for determining the character of the crystal. It is to be noted that sections of uniaxial crystals parallel to the optic axis yield figures like those of biaxial crystals cut perpendicular to the obtuse bisectrix, where the angle is very large.

From these figures the position of the optic axis is determinable and also the direction of vibration of the extraordinary ray, which vibrates in the trace of the plane through the optic axis and the axis of the cone of light, that is, the axis of the microscope.

The inclination of the optic axis to the axis of the cone of light and to the plane of the section can be determined when the angle of aperture of the objective lens is known and the angles subtending various fractions of the radius of the field of view are also known, and the refraction corresponding to the ordinary ray in the mineral is taken into account.

The positive or negative character of the crystal can be determined by means of the mica plate or the quartz wedge, or it may be determined from the interference color in parallel polarized light, where the position of vibration of the extraordinary ray has been located, by noting whether it is the faster or the slower ray. This method may be used when the crystal is too small or has too low birefringence to furnish an interference figure. If the crystal is prismatic, the optic axis will be parallel to the longer axis of the prism.

Biaxial.—The biaxial interference figure in sections cut perpendicular to the acute bisectrix furnishes a means of determining the positive or negative character of the crystal by the use of the mica plate or the quartz wedge. This can also be determined from the figure obtained from a section cut perpendicular, or nearly so, to one optic axis.

The size of the angle between the optic axes can be determined in sections perpendicular to the acute bisectrix, in the same manner as the inclination of the optic axis in a uniaxial crystal section. It is necessary to know the angle of aperture of the lens and the intermediate index of refraction, β, of the mineral. In the interference figure of one axis the value of the angle between the optic axes is indicated in a general way by the curvature of the hyperbola in the 45° position. It is a straight line in this position when the angle is 90°.

In cases where the symmetry of the dispersion of optic axes and bisectrices is recognizable, the system of crystallization of a biaxial crystal is determined, but this case seldom arises in the study of rock sections. The dispersion of the optic axes may be told in favorable cases by the colored edges to the hyperbola in the 45° position.

Crystallographic Character.—Cleavage and Outline of Crystal Sections.—The presence of straight cracks parallel to one or more directions in a mineral section indicates that it is a crystal and not an amorphous substance, like glass or opal. If the crystal is isotropic it belongs to the isometric system.

The outline of a mineral section may be the traces of crystal faces on the cutting plane, or the trace of an irregularly shaped surface not characteristic of the mineral.

Uniaxial Crystals belong to the tetragonal, trigonal, or hexagonal systems, and may be identified crystallographically in sections perpendicular to the optic axis by cleavage or outlines characteristic of one of these systems; in the first case intersecting at 90°, in the second and third cases intersecting at 60° or 120°.

Biaxial Crystals belong to orthorhombic, monoclinic, or triclinic systems, which can be distinguished from one another by the degree of symmetry exhibited in the orientation of the optical bisectrices in the crystal.

In *Orthorhombic Crystals* the bisectrices and intermediate axis Y are parallel to the three crystal axes, a, b, c; consequently the directions of vibration for the doubly refracted light passing through sections of orthorhombic crystals are parallel and perpendicular to the traces of pinacoids and pinacoidal cleavage in sections parallel to any of

these three axes; one is parallel to the traces of prisms or pinacoids in zone in any section parallel to the axis of such zone. The directions of vibration bisect the angle of the prismatic cleavage in sections perpendicular to the cleavage prism or to the planes of symmetry in the prism.

In general the directions of vibration bisect the angles between outlines or cleavages in all sections of orthorhombic crystals cut in the zone of any one of the three crystal axes, that is, at right angles to a plane of symmetry.

The directions of vibration of the components of transmitted light are located by the extinction of the light between crossed nicols, hence the term *extinction* is commonly used instead of the direction of vibration. Thus it may be said that the extinction is symmetrical to two intersecting lines when the planes of vibration bisect the angles between them. Again, the extinction is parallel to a line or cleavage when the direction of vibration is parallel to it. Moreover it is customary to speak of an *extinction angle* when the angle between a direction of vibration and some line of cleavage, outline, or twinning is meant.

In *Monoclinic Crystals* one bisectrix or the intermediate axis Y coincides with the crystallographic axis b, and the plane of symmetry for the crystal form is also a plane of symmetry for the optical properties. Consequently in all sections cut at right angles to the plane of symmetry the extinction lies in the plane of symmetry and is parallel to pinacoids or prisms parallel or perpendicular to this plane, and bisects the angle between all pairs of traces inclined to it. In all other sections of monoclinic crystals this is no longer true.

In *Triclinic Crystals* there are no planes of symmetry, and consequently no symmetrical relation between the directions of vibration and the cleavage traces or outlines of a crystal.

Other, more specific, methods of identifying minerals in thin sections, such as the optical properties of twinned crystals, characteristic forms of crystals, frequent associations, inclusions, or modes of alteration will be described in connection with particular minerals.

Special methods of investigating unmounted thin sections or isolated fragments of crystals for more specific or quantitative optical or chemical determinations may be employed when necessary.

PART II.

DESCRIPTION OF THE ROCK MINERALS.

Introduction.—The minerals are arranged on a chemical basis, but not according to any rigid method of classification, since minerals having like constituents are grouped together among the silicates, though they may not be similar salts of the various silicic acids. That is, polysilicates, metasilicates and orthosilicates are in some cases brought together because the basic metals are similar, and they are closely related or associated in rocks. There is something of a chemical sequence in the succession of mineral species, but the chemical variation in some of the isomorphous groups, such as the pyroxenes and amphiboles, prevents this from being strictly carried out. The arrangement is a chemical and petrographical one, the silicates being placed first because of their petrographical importance.

The method of description followed is nearly the same for all the minerals, except that in case the description of a mineral is long a brief synopsis of the chief characteristics is placed before the more complete account. This is omitted when the description itself is brief.

The characteristics are described in the following order:

Chemical composition.
Alteration.
Crystallographic characters.
Optical properties.
Modes of occurrence.
Resemblances to other minerals.
Laboratory production.

FELDSPAR GROUP.

COMPOSITION: $KAlSi_3O_8$ — Or
$NaAlSi_3O_8$ — Ab
$CaAl_2Si_2O_8$ — An
$BaAl_2Si_2O_8$ — Ce

TRICLINIC (pinacoidal) and PSEUDO-MONOCLINIC.

Twinning: albite law, twinning plane and composition plane (010). Pericline law, (twinning) axis, *b*; composition plane, the rhombic section. Carlsbad law, twinning axis, *c*; composition plane (010). Baveno law, twinning plane and composition plane (021). Manebach law, twinning plane and composition plane (001).

Cleavage: (001) perfect, (010) somewhat less so. Other cleavage parallel to (110) or $(1\bar{1}0)$ not often developed. Parting parallel to (100) rare, also parallel to $(\bar{7}01)$ or $(\bar{8}01)$ in some occurrences. *Fracture:* conchoidal to uneven. Brittle. H. = 6 to 6.5.

Specific gravity varies with the composition.

Orthoclase	2.54–2.56	
Albite, Ab	2.605	Day (artificial feldspars)
Ab_3An_1	2.649	"
Ab_2An_1	2.660	"
Ab_1An_1	2.679	"
Ab_1An_2	2.710	"
Ab_1An_5	2.733	"
Anorthite, An	2.765	"
Celsian, Ce	3.34	

OPTICAL PROPERTIES. Optical orientation, indices of refraction, and angle between the optic axes vary with the chemical composition of the feldspars.

	α	β	γ	$\gamma-\alpha$
Orthoclase (St. Gothard)	1.519	1.524	1.526	0.007
Albite (Grande Caldeira, Azores)	1.5250	1.5306	1.5314	0.0064
Anorthite (St. Clement)	1.574	1.579	1.586	0.012
Celsian (Jakobsberg)	1.5837	1.5886	1.5940	0.010

Color: colorless in thin section. In thicker crystals colorless, gray, white, light shades of yellow, pink, green, blue. Sometimes dark shades. *Luster:* vitreous, pearly, dull.

Chemical Composition.—The feldspars are silicates, or alumino-silicates, of aluminium and of potassium, sodium or calcium, or of all three, and rarely of barium. The group may be looked on as a series of mixed salts, an isomorphous series, the four pure salts being

known, namely, the potash-feldspar, microcline-orthoclase, the soda-feldspar, albite, the lime-feldspar, anorthite, and the barium-feldspar, celsian.

Orthoclase,	$KAlSi_3O_8$,	Or;	or	$K_2O \cdot Al_2O_3 \cdot 6SiO_2$,	2Or
Albite,	$NaAlSi_3O_8$,	Ab;	or	$Na_2O \cdot Al_2O_3 \cdot 6SiO_2$,	2Ab
Anorthite,	$CaAlAlSi_2O_8$,	An;	or	$CaO \cdot Al_2O_3 \cdot 2SiO_2$,	An
Celsian,	$BaAlAlSi_2O_8$,	Ce;	or	$BaO \cdot Al_2O_3 \cdot 2SiO_2$,	Ce

In rocks all possible mixtures of Ab and An are known to occur in zonally built feldspars, and many of the possible mixtures have been noted as simpler crystals. The synthetical work of Day has demonstrated that any mixture of Ab and An can crystallize in homogeneous crystals. In rocks various mixtures of Or and Ab occur in apparently homogeneous crystals, but often albite crystallizes separately in the presence of orthoclase; and lime-soda-feldspars generally crystallize separately from solutions containing orthoclase. Nevertheless Day has produced homogeneous crystals of lime-potash-feldspars, and has demonstrated the isomorphism of the whole series, including potassium-, sodium-, and calcium-feldspars. Mixtures of potassium- and barium-feldspars occur sparingly in rocks, and still more rarely barium-calcium-sodium-feldspar.

According to the composition the following varieties have been recognized:

Orthoclase (microcline), $KAlSi_3O_8$, with very little Na in some cases.
Soda-orthoclase, $(K,Na)AlSi_3O_8$.
Soda-microcline (anorthoclase), $(Na,K)AlSi_3O_8$.
Albite (Ab), $NaAlSi_3O_8$.
Lime-soda-feldspar series, $\begin{cases} n(NaAlSi_3O_8), \\ m(CaAlAlSi_2O_8). \end{cases}$
Anorthite (An), $CaAlAlSi_2O_8$.
Hyalophane, $\begin{cases} n(KAlSi_3O_8), \\ m(BaAlAlSi_2O_8). \end{cases}$
Celsian (Ce), $BaAlAlSi_2O_8$.

The lime-soda-feldspar series has been subdivided as follows:

Albite,	$Ab_1An_0 - A_6An_1$.
Oligoclase,	$Ab_6An_1 - Ab_3An_1$.
Andesine,	$Ab_3An_1 - Ab_1An_1$.
Labradorite,	$Ab_1An_1 - Ab_1An_3$.
Bytownite,	$Ab_1An_3 - Ab_1An_6$.
Anorthite,	$Ab_1An_6 - Ab_0An_1$.

The chemical compositions by percentage weights are:

	SiO_2	Al_2O_3	K_2O	Na_2O	CaO	BaO
Or.	64.7	18.4	16.9	—	—	—
Ab_1An_0	68.7	19.5	—	11.8	0.	—
Ab_6An_1	64.9	22.1	—	10.0	3.0	—
Ab_3An_1	62.0	24.0	—	8.7	5.3	—
Ab_1An_1	55.6	28.3	—	5.7	10.4	—
Ab_1An_3	49.3	32.6	—	2.8	15.3	—
Ab_1An_6	46.6	34.4	—	1.6	17.4	—
Ab_0An_1	43.2	36.7	—	0.	20.1	—
Ce	32.0	27.2	—	—	—	41.8

The percentages of Na_2O, CaO, Al_2O_3, and SiO_2 to within 0.1 of a per cent may be found by means of the diagram Fig. 1. To the values read from the scale 10 per cent. is to be added in the case of Al_2O_3, and 40 per cent. in the case of SiO_2.

The chemical analysis of feldspar material may be the analysis of a homogeneous crystal, or of a zonally variable crystal, or of an intergrowth of potash-feldspar with one of the albite-anorthite series, and the actual case can only be determined by microscopical study of the material analyzed. This fact is important in a discussion of the chemical and optical relationships in feldspars.

The percentage weights of the oxides for any feldspar Ab_nAn_m are found from the proportionate molecular weights in $n(Na_2O \cdot Al_2O_3 \cdot 6SiO_2) + m2(CaO \cdot Al_2O_3 \cdot 2SiO_2)$. That is, $524n + 2 \times 278m =$ total lime-soda-feldspar. The molecular weight of Ab is to that of An as 1:1.061; consequently when the method of determining the value of n and m is not exact the error of assuming equal molecular weights for Ab and An is within the limits of the method, and it will be sufficiently accurate to consider the relative weights of Ab and An in a feldspar as proportional to n and m. Thus Ab_3An_2 would be $\frac{3}{5}$ albite and $\frac{2}{5}$ anorthite.

Alteration.—The alkalic feldspars are not attacked by hydrochloric acid. The more calcic feldspars are decomposed by the acid in proportion to their content of calcium. Thus oligoclase and andesine are not attacked; labradorite is slightly acted upon; bytownite and anorthite are decomposed with the separation of gelatinous silica. In the rocks the more calcic feldspars are more readily decomposed than the more alkalic feldspars in general. The process of alteration is not always the same in feldspars of like composition in different instances, and is also different in different kinds of feldspars.

Potash-feldspar commonly alters to muscovite (sericite), or kaolin and quartz. The same is true of albite. The alteration of the more

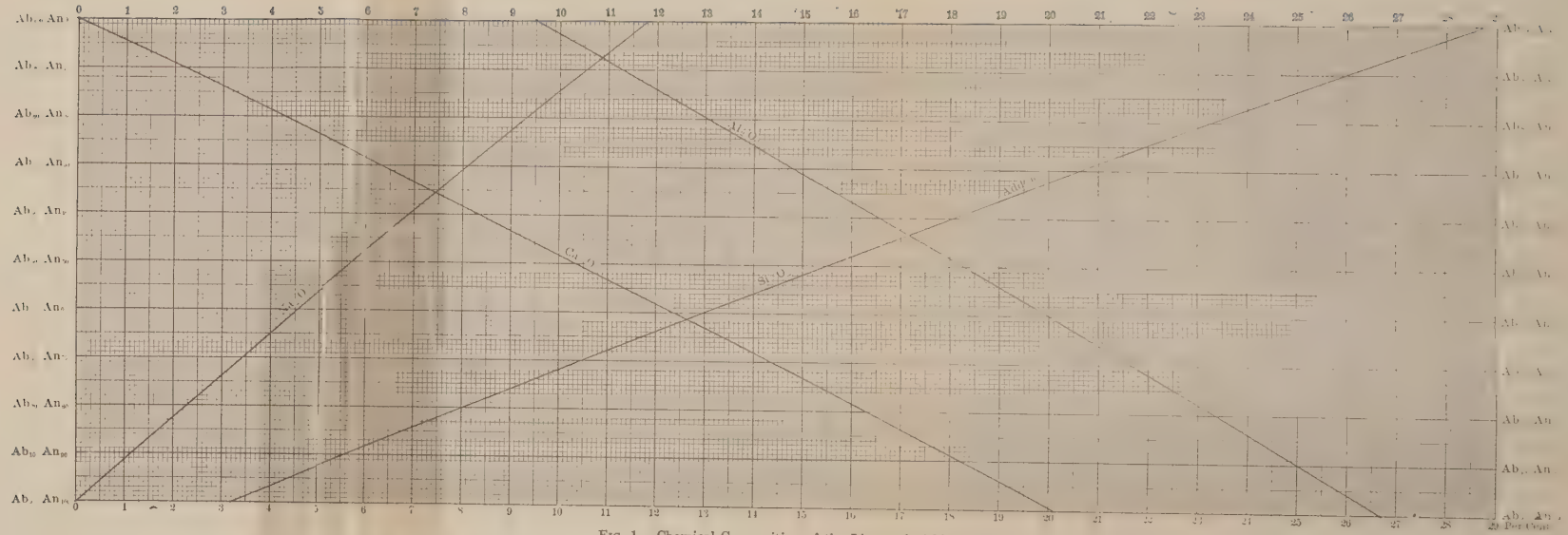

FIG. 1.—Chemical Composition of the Lime-soda-feldspars.

Percentages of Na_2O, CaO, Al_2O_3, and SiO_2 in albite-anorthite feldspars. Add 10% to the reading for Al_2O_3 and 40% to the reading for SiO_2.

sodic feldspars is similar to that of albite with the accompaniment in some cases of calcite. The more calcic feldspars often alter into a mixture of minerals called saussurite. These minerals may be zoisite and secondary albite, or in addition amphibole, garnet, chlorite, epidote, etc. Less frequently they alter to hydrargillite, as in certain basalts. In the more alkalic rocks the highly sodic feldspars alter to zeolites. The alteration of feldspars may be accompanied by the introduction of magnesium and iron and the formation of various ferromagnesian silicates.

Crystallographic Characters.

	$a:b:c$	α	β	γ	$001 \wedge 010$
Orthoclase, Microcline,	0.6585:1:0.5554	90°	116° 3′	90°	90° / 89° 30′
Hyalophane,	0.6584:1:0.5512	90°	115° 35′	90°	90°
Celsian,	0.657 :1:0.554	90°	115° 2′	90°	90°
Albite,	0.6335:1:0.5577	94° 3′	116° 29′	88° 9′	86° 24′
Oligoclase,	0.6321:1:0.5524	93° 4′	116° 23′	90° 5′	86° 8′
Andesine,	0.6357:1:0.5521	93° 23′	116° 29′	89° 59′	86° 14′
Labradorite,	0.6377:1:0.5547	93° 31′	116° 3′	89° 54½′	86° 4′
Anorthite,	0.6347:1:0.5501	93° 13′	115° 55′	91° 12′	85° 50′

Forms.—Microcline and feldspars of the albite-anorthite series crystallize in triclinic forms, and the apparently monoclinic orthoclase may be considered as a microcline in which the polysynthetic twinning is so minute as to be submicroscopic. The habit of the various feldspars is so much the same, whether triclinic or pseudo-monoclinic, that a crystallographic description of one serves for all, with certain modifications. The description will be stated in terms of the triclinic forms, and can be altered to apply to the apparently monoclinic orthoclase.

Several types of habit occur in the rock-making feldspars: (*a*) equidimensional, (*b*) tabular, (*c*) prismatic. The crystal forms, or planes, involved are chiefly the same in these three kinds of habit, with some variation in the grouping. The forms which are most commonly developed are: basal pinacoid, *c* (001), second pinacoid, *b* (010), rarely the first pinacoid, *a* (100), in some lime-soda-feldspars; commonly the pinacoids of the third kind, *m* (110), *M* ($1\bar{1}0$), also pinacoids of the second kind, *x* ($\bar{1}01$), *y* ($\bar{2}01$), rarely *n* (021), *n′* ($0\bar{2}1$), *z* (130), *z′* ($1\bar{3}0$), and *o* ($\bar{1}11$), *o′* ($\bar{1}\bar{1}1$).

The commoner types of habit for orthoclase are shown in Figs. 2, 3, 4, 5. The albite-anorthite feldspars in rocks are less perfectly

bounded by crystal planes and their forms have not been so clearly made out. The simpler types are shown in Figs. 6, 7, 8, 9.

Twinning.—The feldspars are sometimes untwinned crystals, but in most cases they are twinned, the twinning being in one, two, and

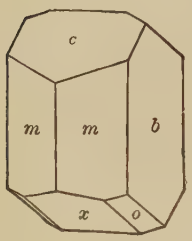

FIG. 2.

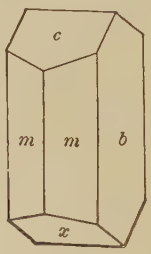

FIG. 3.

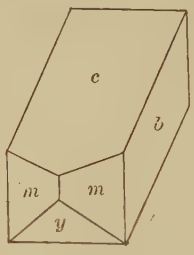

FIG. 4.

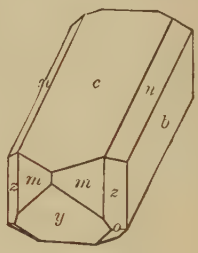

FIG. 5.

often three directions in the same crystal. There are three kinds that are common, two that are much less so, and one that is extremely rare.

Carlsbad.—Twinning axis, crystal axis *c*; composition plane (010), sometimes an irregular surface, the two parts being side by side as when (010) is the composition plane, very rarely in contact parallel to (100), as in the potash-oligoclase-albite from Kilimanjaro and in

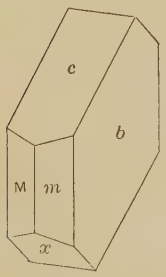

FIG. 6.

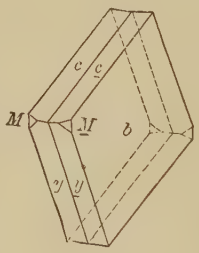

FIG. 7.

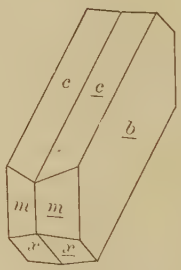

FIG. 8.

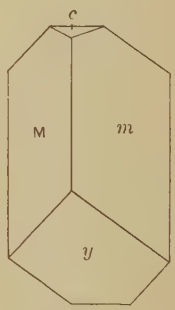

FIG. 9.

that of rhombenporphyry in Norway, Fig. 12. Carlsbad twins consist usually of two parts only, and are not repeated in alternate lamellæ. The common form of Carlsbad twins is shown in Fig. 10. Since the faces *c* (001) and *x* ($\bar{1}01$) make almost the same angle with the axis *c*, but in opposite directions, it happens that Carlsbad twins of orthoclase sometimes take the form shown in Fig. 11, in which case the crystal may be mistaken for an untwinned feldspar. The direction

of the basal cleavage, and the difference in the optical orientation, in the two parts serve to identify the twinning. In all sections cut perpendicular to (010) in orthoclase the extinction angle in each part of the Carlsbad twin is 0°. But in such sections in all other feldspars the extinction angles in each part of the Carlsbad twins are different

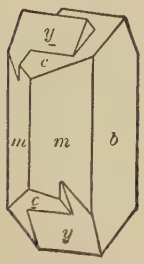

Fig. 10.

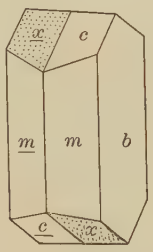

Fig. 11.

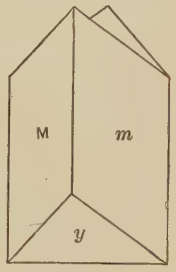

Fig. 12.

except when the section is parallel to (100), the plane of symmetry for the twinned parts. The rarer form of this twinning, where the composition plane is (100), is shown in Fig. 12.

Baveno.—Twinning plane (021); composition plane the same. This is diagonal to the square prism whose sides are (001)(010), Fig. 13. This mode of twinning is easily recognized in thin sections cut across the prism, the composition plane is diagonal to the cross-section, and the planes of the optic axes in the two parts are at right angles to one another (Fig. 14). Occasionally the two parts cross one another, mak-

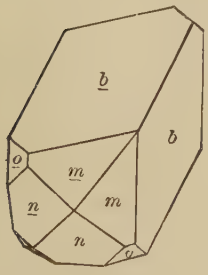

Fig. 13.

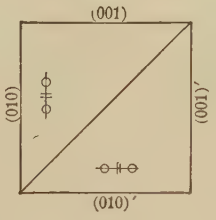

Fig. 14.

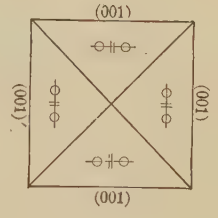

Fig. 15.

ing a fourling (Fig. 15). This mode of twinning is not so common as the Carlsbad. In rare instances it is found in combination with Carlsbad twinning.

Manebach.—Twinning plane (001); composition plane the same. This occurs in square prismatic crystals elongated parallel to the *a* axis (Fig. 16), and in tabular crystals flattened parallel to (001), also in crystals tabular parallel to (010). It is recognized by having the basal cleavage in the same position in both parts. It is more frequently met with than Baveno twinning, especially in microscopic prisms of orthoclase in spherulitic growths. In such crystals it might easily be confused with Baveno twinning or with albite twinning.

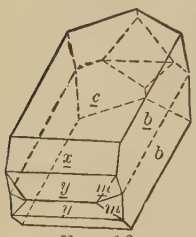

FIG. 16.

Albite Law.—Twinning plane (010); composition plane the same. This usually occurs repeated many times in one crystal, producing thin lamellæ parallel to (010). This can only occur in triclinic feldspars since (010) is a plane of symmetry in pseudo-monoclinic ones. It may

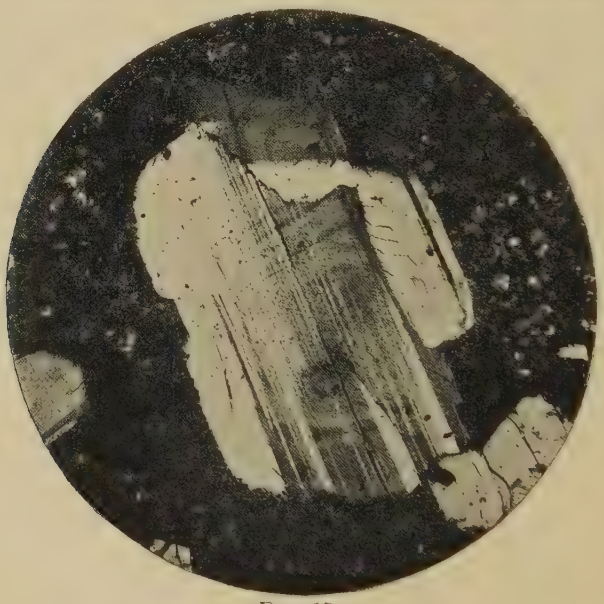
FIG. 17.

in fact be the cause of the apparent monosymmetric character of orthoclase, as stated in another place. The alternate inclination of the basal cleavage on the twinned lamellæ produces striations on the basal plane (001) of crystals twinned in this manner. In general the lamellæ are thicker in the more calcic feldspars and thinner in the more sodic ones, and are exceedingly thin in microcline. But there are many cases in which no such difference is recognizable, and the lamellæ in calcic feldspars may be of microscopical thinness.

The form of an albite twin is shown in Figs. 7 and 8. When the twinning is repeated many times the alternate lamellæ have reversed optical orientation, and a thin section of such a twin between crossed nicols appears striped in bands of light and shade (Fig. 17). The lamellæ do not necessarily traverse the crystal from one side to another. They may wedge out or terminate abruptly at any place. They appear distinct and sharp edged in sections perpendicular to the plane of twinning (010). They are less clearly defined in sections inclined to this plane, and do not appear at all in those parallel to it. This kind of twinning is the commonest, being found alone and in combination with pericline and Carlsbad twinning in nearly all occurrences of lime-soda-feldspar and of microcline, and being supposed to be present submicroscopically in orthoclase.

Pericline.—Twinning axis the crystal axis *b*; composition plane a rhombic section whose position in feldspars of different composition shifts with the composition, as shown in Figs. 18, 19. The inclination of the trace of this plane on (010) for different feldspars is given in Fig. 20. The position ranges from $-18°$ in anorthite to $+21°$ in albite,

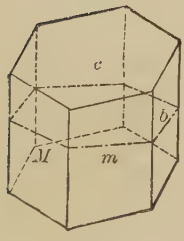

Fig. 18.

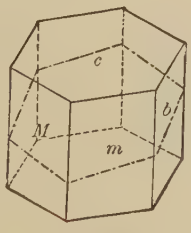

Fig. 19.

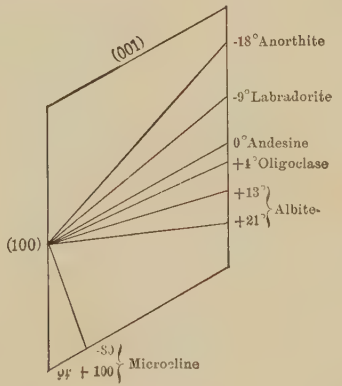

Fig. 20.

and is $-80°$ in microcline. In all feldspars it is nearly perpendicular to (010). The form of a simple pericline twin of albite feldspar is shown in Fig. 21. This twinning is usually repeated a number of times in one crystal, producing twinned lamellæ as in albite twinning. In sections perpendicular to (010) the two sets of lamellæ are nearly at right angles to one another as in Fig. 22. In most cases the pericline lamellæ are less numerous than the albite lamellæ. But in microcline both are very abundant, are very thin,

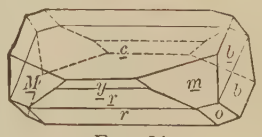

Fig. 21.

and wedge out in short lengths, producing the appearance of a grating or a plaid (Fig. 23).

Other modes of twinning to the number of 13 have been described on feldspars from different localities, but they are rarely met with and need not be described in this place. In some cases they may be chance groupings.

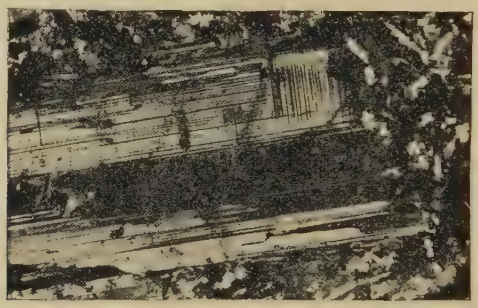

Fig. 22.

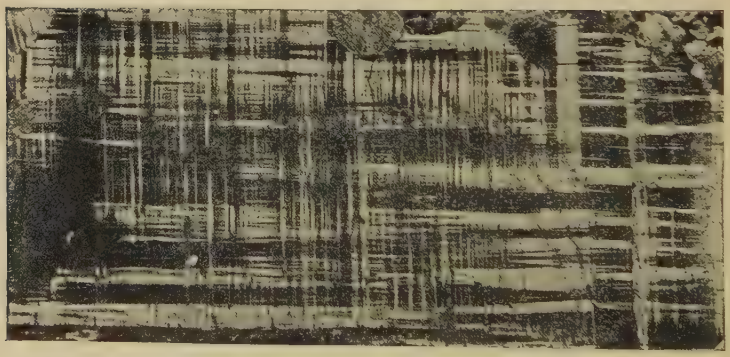

Fig. 23.

Crystal Habit.—Euhedral. *Equidimensional* or *equant* feldspars occur mostly as phenocrysts in porphyries. Those most commonly met with are potash-feldspars, less frequently lime-soda-feldspars in dacite and andesite, sometimes in anorthite. Feldspars with equidimensional habit are more often megascopic crystals.

Tabular forms are more common than equant ones. Megascopic crystals of potash-feldspar are generally thick tables, from 2 to 4 times as broad as thick, and usually in Carlsbad twins. Those of lime-soda-feldspar are frequently thinner, sometimes $\frac{1}{10}$ as thick as broad.

Tabular microscopic crystals of potash-feldspar are often very thin as compared with their breadth, and may be Carlsbad twins or simple crystals. The plane of flattening is almost always (010). They occur as microlites in rock glasses. Microscopic tabular euhedral crystals of lime-soda-feldspars are rarely seen. They are developed in some preparations of these feldspars made in the laboratory, but are not common in the igneous rocks.

Prismatic crystals of potash-feldspar are common both as megascopic phenocrysts and as microscopic crystals. They are usually elongated parallel to *a* and may be simple crystals, or Baveno or Manebach twins; less frequently Carlsbad twins. The megascopic crystals are generally short, thick prisms. Microscopic crystals are usually longer and more slender.

Prismatic forms of lime-soda-feldspars are still more common, and microscopic prisms of these feldspars are the most frequent forms. They are usually twinned according to the albite law. The smaller the crystals the more slender the prisms as a rule. An unusual habit is developed in porphyritic crystals of soda-microcline or oligoclase-microcline in certain rocks of the Christiania region, the so-called "rhombenporphyries." It is produced by the combination of *m* (110), $M(1\bar{1}0)$ with $y(\bar{2}01)$ and *c*(001), Fig. 9, which may be twinned according to the Carlsbad law, Fig. 12. These rhomboid prisms are commonly flattened parallel to the first pinacoid (100) by the modification of the angle between *m* and *M*, which may be 45° according to Brögger, but which is considered by Mügge to be made by the development of faces (950) and $(9\bar{5}0)$.

In general it may be said that equidimensional forms occur oftenest in potash-feldspar and in megascopic crystals, and that the microscopic forms of this feldspar are usually thin plates. Whereas megascopic crystals of lime-soda-feldspar are oftenest tabular and the microscopic forms prismatic.

Subhedral forms of feldspar may have any of the types of habit described for euhedral forms with modifications due to partial interference with the complete development of outward crystal form, or to subsequent destruction of the outward form by partial solution or by fracturing. To the first case belong phenocrysts of feldspar that have grown in contact with other crystals, and also non-porphyritic feldspars that have grown against other crystals in some directions and freely in the rock liquid in others. The latter are often met with among the lime-soda-feldspars in rocks containing potash-feldspar and quartz which did not crystallize until after the lime-soda-feldspars.

There are many instances in which the perfect development of crystal form has been hindered by the viscosity of the liquid rock producing subhedral forms. These are commonly met with in glassy rocks and may be single crystals or aggregations of many. The indi-

Fig. 24.

vidual crystals are usually microscopic, but the aggregations are often megascopic.

Orthoclase develops in prisms elongated in the direction of the *a* axis, sometimes twinned according to the Manebach law. The prisms

curved and forked at a slight angle into two prisms, each twinned as in the upper half of Fig. 24. In some cases the twinned prism is branched with spurs projecting at an angle of 64° to the main prism, as in the lower half of Fig. 24. These branches are elongated parallel to the *c* axis, Fig. 25. They may be thin and curved so as to be parallel to the main prism, Fig. 26. In such cases the main prisms have the

Fig. 25.

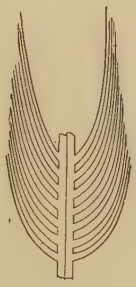

Fig. 26.

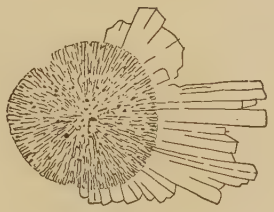

Fig. 27.

fastest ray, *X*, nearly parallel to their length, while the branching prisms have *Y* or *Z* almost parallel to their length according to the position of the plane of the optic axes. In some instances the end of a long slender prism broadens out in a spurred leaflike form tabular parallel to (010). Such crystals of orthoclase occur in obsidian.

Another form of subhedral orthoclase is found in short prisms which radiate from a point and constitute a spherulite bristling with crystals of different lengths, which appear in section as in Fig. 27. These feldspars are not twinned.

Lime-soda-feldspars occur in subhedral forms of great variety due largely to the tendency to produce prismatic or fibrous crystals as the liquid becomes more viscous.. Microscopic feldspars which have commenced to grow as equant, tabular, or stout prismatic forms often finish by sprouting at the corners in thin fibrous prisms all parallel to one direction, the *a* axis. According to the proportions of the earlier crystal and the length and number of the fibrous prisms the resulting shapes appear in section as in Fig. 28. In some cases the feldspar appears as a bundle of fibers slightly curved, or as single fibers. These are less frequently

Fig. 28.

aggregated in spherulitic groups than orthoclase is. But such aggregations are readily obtained in laboratory productions of all mixtures of lime-soda-feldspars. In these spherulites the crystals are sometimes in slender prisms occasionally flattened at the extremities. In other cases they are aggregates of thin plates, tabular parallel to (010), and bounded by various planes.

Subhedral feldspars whose forms have been modified by partial solution occur as phenocrysts in some porphyries. They are not common, however. Instances are known where such solution, producing more or less complete rounding, has occurred on one feldspar several times during its crystallization. This is shown by the shape of the zones of different optical orientation and chemical composition in some zonally built feldspars (Fig. 44, p. 229). Parts of feldspar crystals that have broken before the final solidification of the rock are subhedral or anhedral.

Anhedral feldspars occur of various types, approaching equant, tabular, or prismatic forms, but without crystal faces. Or they may be quite irregular in shape. Often they appear to be euhedral or subhedral when strictly they are neither. The appearance is due to pronounced zonal structure which makes the crystal seem to have definite form, when close examination of the outer zone shows an anhedral surface and an irregular outline in sections.

Anhedral forms are common in most holocrystalline feldspathic rocks, and often occur with subhedral and euhedral forms.

Cleavage. — Feldspar usually exhibits distinct cleavage which appears in thin section as straight cracks, often interrupted and seldom extending the full length of the crystal. The cleavage parallel to (001) is generally more distinct than that parallel to (010), but the distinctness of the cleavage cracks and the angle between the two sets vary with the position of the plane of the thin section. In some orthoclase and microcline there is a parting or cleavage parallel to a pinacoid of the first kind ($\bar{h}0l$), whose exact position is not definitely known. It is about ($\bar{1}\bar{5}.0.2$), ($\bar{7}01$), or ($\bar{8}01$). It is sometimes developed in soda-microcline, but has not been observed in the lime-soda-feldspars. There is also in some cases a cleavage parallel to (110) and ($\bar{2}01$), and less often a parting parallel to (100). The feldspars in certain lavas are quite free from cleavage cracks in thin sections, and are traversed by few curved or irregular fracture lines, just like those commonly seen in quartz. In such cases unstriated feldspar may be easily mistaken for quartz.—*Fracture* uneven in directions other than those of cleavage and poorly developed in most cases. In the

glassy feldspars of some lavas and of some coarsely crystallized rocks—oligoclase of Bakersville, N. C.—the fracture is conchoidal as in quartz.

H. = 6–6.5. *Specific gravity* varies with the chemical composition. Sp. gr. = 2.54–2.56 (orthoclase); on pure artificial feldspars Sp. gr. = 2.605 (Ab), 2.649 (Ab_3An_1), 2.660 (Ab_2An_1), 2.679 (Ab_1An_1), 2.710 (Ab_1An_2), 2.733 (Ab_1An_5), 2.765 (An). The determinations on crystals from rocks are usally affected by the presence of inclu-

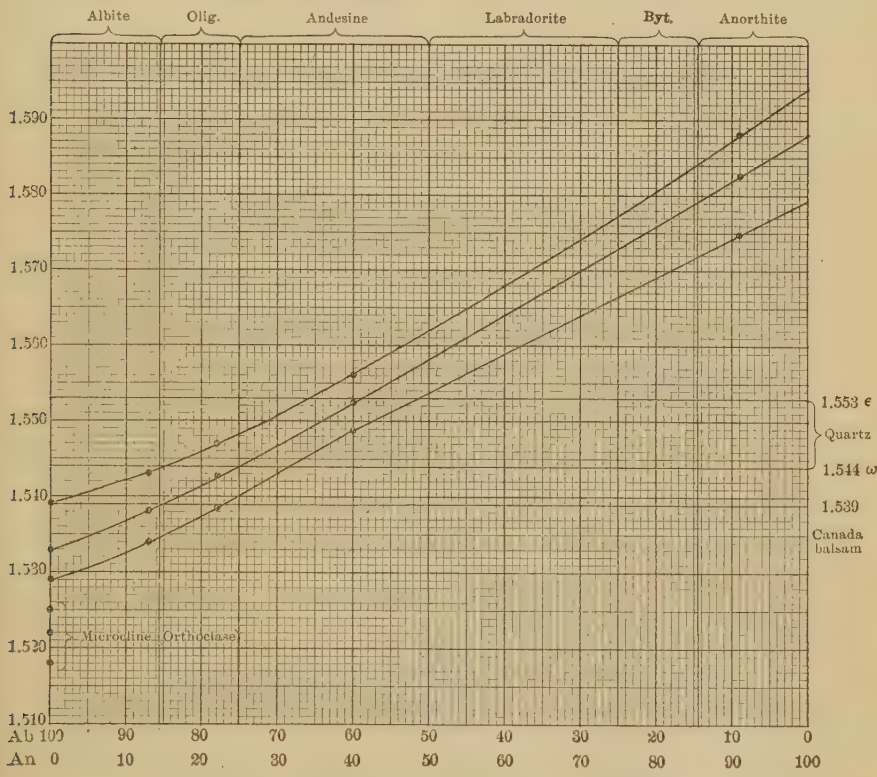

Fig. 29.—Indices of Refraction of the Feldspars.

sions, or by lack of chemical homogeneity in the feldspar. Sp. gr. = 2.593 (barium-orthoclase, $Or_{19}Ce_1$), 2.645 ($Or_{10}Ce_1$), 2.725 (hyalophane, Or_4Ce_1), 2.756 (Or_3Ce_1), 2.818 (Or_7Ce_3), 3.384 (celsian, Ce).

Optical Properties.—Colorless in thin section, but sometimes clouded and colored by inclusions of secondary origin or of primary origin. Feldspars vary in refraction according to the composition, potash-feldspar and soda-feldspar having lower refraction than Canada balsam, these and oligoclase being lower than quartz, andesine about

the same as quartz, and labradorite and anorthite having higher refraction than quartz; the slight differences in some cases being detected by the Becke method. However, on account of the double refraction in all of these minerals the case is not simple, and the exact relations between the different indices of refraction of each mineral and the highest and lowest refraction in quartz are stated graphically in the diagram Fig. 29. The abscissas represent proportions of albite (Ab) and anorthite (An); the ordinates, indices of refraction derived from the following data:

	α_y	β_y	γ_y	
1. Albite, $Ab_{100}An_0$, Amelia Co., Va.	1.5292	1.5331	1.5393	Viola
2. Albite, $Ab_{100}An_0$, Lakous, Crete	1.5290	1.5333	1.5386	Viola
3. Oligoclase-albite, $Ab_{87}An_{13}$, Soboth	1.5337	1.5376	1.5429	Becke
4. Oligoclase, $Ab_{78}An_{22}$, Bakersville, N. C.	1.5389	1.5431	1.5469	Offret
" " " "	1.5388	1.5428	1.5463	Tertsch
5. Andesine, $Ab_{60}An_{40}$, Roche Sauve, Ardèche	1.549	1.553	1.556	Lévy and Lacroix
6. Anorthite, Ab_9An_{91}, Vesuvius	1.5752	1.5833	1.5884	Viola
	ω		ε	
Quartz	1.544		1.553	
Canada balsam	1.539			

A study of the diagram shows that when Canada balsam is the standard of reference, andesine and more calcic feldspars have higher refraction than balsam; the refraction of oligoclase is in part higher than balsam, and most varieties of oligoclase have the same refraction as balsam in certain positions and also higher and lower refraction in other positions. For the most part albite exhibits lower refraction than balsam, but even pure albite has the same refraction as balsam when it exhibits the highest; and all albite in certain positions exhibits higher refraction than balsam. It follows from this that the lime-soda-feldspars which in some sections have the same refraction as balsam may be albite or oligoclase. But when most of the sections of such feldspar have higher refraction than balsam the feldspar is probably oligoclase; when most have lower refraction it is probably albite. It is to be remembered that other cement than Canada balsam is sometimes used in the mounting of rock sections, which may lead to confusion in their identification by this method.

When quartz is used as the standard of comparison it is to be noted that the refraction of a quartz section varies with its position with respect to the direction of vibration of the polarized light, except in sections cut perpendicular to the optic axis, when the refraction is constant, and is 1.544 that of the ordinary ray. In the case of

any other section it is always possible to rotate the quartz so that the transmitted light passes through as ordinary rays with a refraction of 1.544. In such a position the direction of vibration of the slowest ray is parallel to that of the light coming from the polarizer. It is possible then to obtain from quartz a more definite standard of comparison than Canada balsam, whose refraction varies somewhat with its dryness. But in most sections of quartz the definite refraction of 1.544 is obtained in only one position. Numerous sections of quartz in one rock section in a measure counterbalance this disadvantage.

A study of the diagram shows that the refraction of labradorite and more calcic feldspars is always higher than the highest of quartz, and that the refraction of albite is always lower than the lowest of quartz. With oligoclase and andesine there is overlapping of their limits of refraction and those of quartz. Most oligoclase has lower refraction than the lowest of quartz, 1.544, while most andesine has higher refraction than the lowest of quartz. In general, andesine and quartz have nearly the same range of refraction,

An approximate determination of the mean index of refraction of feldspar fragments, obtained by crushing the crystals, may be made by immersing them in liquids whose refraction can be modified and determined in the manner described on page 117. And this method may be used for an approximate determination of the kind of feldspar present in a rock when this is not feasible by one of the methods to be described in subsequent paragraphs. For this purpose a series of liquids with known refraction corresponding to different varieties of feldspars may be prepared and kept in closely stoppered phials or dropping-bottles to prevent evaporation and change of concentration. On account of their miscibility in all proportions and their nearly equal rates of evaporation, cedar oil with $n_y = 1.516$, clove oil with $n_y = 1.544$, and cinnamon oil with $n_y = 1.605$, are convenient. Another series of liquids which may be used is: monochlorobenzene, 1.523; clove oil, 1.544; æthylene bromide, 1.536; nitrobenzene, 1.554; monobromobenzene, 1.561; and mixtures of the latter with bromoform, 1.588. The refraction of the mixed liquid may be determined on a refractometer or it may be made to correspond to the refraction of crystals whose refraction has already been determined.[1]

Data with respect to the indices of refraction and the angle between the optic axes in different kinds of feldspars are given in the accompanying table.

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[1] Wright, F. E. Am. Jour. Sci., Vol. 21, 1906, p. 361.

INDICES OF REFRACTION OF FELDSPARS.

	α	β	γ	$\gamma-\alpha$	$2V$	$2E$	Temp.	
Potash-feldspar.								
Adularia, St. Gothard	1.5190_y	1.5237_y	1.5260_y	0.0070_y	69° 43′$_y$	121° 6′$_y$	18° C.	Des Cloizeaux
" " "						$X\wedge a$ 5° 18′$_r$,	5° 44′$_b$	
" " "	1.5181_y	1.5223_y	1.5243_y	0.0062_y	69° 1′$_y$	119° 1′$_y$	18° C.	" "
	1.5192	1.5230	1.5246	0.0054	66° 5′	106° 7′		Kohlrausch
" Zillerthal	1.5195	1.5233	1.5253	0.0058	71° 43′	126° 22′	16°.5 20°.5	Zimmermann
Sanidine, Wehr, near Laach	1.5170_r	1.5239_r	1.5240_r	0.0070_r	13° 34′$_r$	20° 45′$_r$	18° C.	Des Cloizeaux
	1.5265_b	1.5355_b	1.5356_b	0.0091_b	11° 51′$_b$	Axial plane + $(010)_r$ 18° 14′$_b$	18° C.	" "
" " " "	—					Axial plane ∥ $(010)_b$ $X\wedge a$ 4° 17′$_r$,	4° 45′$_b$	" "
" Eifel	1.5206	1.5250	1.5253	0.0047	28° 58′	41° 6′	21° C.	Kohlrausch
" Dockweiler, Eifel	1.520278_y	1.524853_y	1.524972_y	0.004694_y		$X\wedge a=5°_y$	22° C.	Offret
Microcline Gasern, n. Meissen	1.5224_y	1.5264_y	1.5295_y	0.0071_y	83° 41′$_y$	—	—	Ussing
" Cala Francese, Sardinia	1.5185	1.5227	1.5249	0.0064	71° 37′.5	—	—	Riva
" "	1.5194	1.5236	1.5263	0.0069	77° 15	—	—	"
" Palkina, Ural	1.5183	1.5220	1.5248	0.0065	81° 51′.5	—	—	"
" Narestö, Norway	1.523_y	1.526_y	1.529_y	0.006_y	—	—	—	Lévy and Lacroix
Soda-potash-feldspars.								
Soda-microcline, Vidalenc, Mont Dore	1.5215_y	1.5266_y	1.5272_y	0.0057_y	32° 8′	50°	*Calc.*	Fouqué
" Porte Senso, Sardinia	1.5224_y	1.5280_y	1.5290_y	0.0066_y	—	—	—	Riva
" Castello Branco, Fayal	1.5224_y	1.5281_y	1.5289_y	0.0065_y	49° 8′	79°	*Calc.*	Fouqué
" Quatre Ribeiras, Terceira, Azores	1.5234_y	1.5294_y	1.5305_y	0.0071_y	45° 37′ 40″	—	*Calc.*	"
" Grande Caldeira, Terceira, Azores	1.5250_y	1.5306_y	1.5314_y	0.0064_y	42° 56′	—	*Calc.*	"
Soda-lime-feldspars.								
Albite, Amelia Co., Va.	1.5285	1.5321	1.5387	0.0102	77° 39′	—	—	Becke
" " " "	1.5292_x	1.5331_y	1.5393	0.0101	76° 36′	—	—	Viola
" Lakous, Crete	1.5290	1.5333	1.5386	0.0096	84° 4′	—	—	"

Soda-lime-feldspars.								
Albite, Carrara	1.5282	1.5323	1.5389	0.0107	76° 55′	—	—	Viola
" Schmirn	1.5287_y	1.5331_y	1.5392_y	0.0105_y	$80° 58'_y$	—	—	Zimmermann
" Narestö, Norway	1.532	1.534	1.540	0.008	—	—	—	Lévy and Lacroix
Oligoclase-albite, Soboth	1.5337	1.5376	1.5429	0.0092	—	—	—	Becke
Oligoclase, Bamle, Norway	1.534	1.538	1.542	0.008	—	—	—	Lévy and Lacroix
" "Mexico,"								
? Bakersville, N. C.	1.5373_y	1.5415_y	1.5457_y	0.0084_y	$90°_y$	—	*Calc.*	Fouqué
" Bakersville, N. C.	1.5389_y	1.5431_y	1.5469_y	0.0080_y	$88° 16'_y$	—	—	Offret
Andesine, Roche Sauve, Ardèche	1.549_y	1.553_y	1.556_y	0.007_y	—	—		Lévy and Lacroix
" "	1.5548_y	1.5578_y	1.5625_y	0.0077_y	$80° 40'_y$	—	*Calc.*	Fouqué
Labradorite, Labrador	1.554	1.557	1.562	0.008				
" Sta. Lucia, Pico	1.5545_y	1.5589_y	1.5634_y	0.0089_y	$77° 24'_y$	$132°_y$	*Calc.*	"
" Lava 1720, Pico, Azores	1.5556_y	1.5563_y	1.5631_y	0.0075_y	$77° 38'_y$	—	*Calc.*	"
" North Crater, Pico	1.5562_y	1.5582_y	1.5631_y	0.0069_y	77° 6′	—	*Calc.*	"
" Vellas, St. Jorge, Azores	1.5597_y	1.5628_y	1.5677_y	0.0080_y	76° 16′	—	*Calc.*	"
" Capello, Fayal	1.5611_y	1.5639_y	1.5689_y	0.0078_y	77°	—	*Calc.*	"
" La Besseyre, Hte. Loire	1.5617	1.5647	—	—	—	—	*Calc.*	"
Anorthite, St. Clément,								
" Puy de Dôme	1.574	1.581	1.586	0.012	—	—	—	Lévy and Lacroix
" Mte. Somma	1.5757_y	1.5837_y	1.5884_y	0.0127_y	77° 18′	147°	*Calc.*	Fouqué
" Vesuvius	1.5752	1.5833	1.5884	0.0132	103° 4′	—	—	Viola
Potash-barium-feldspar.								
	Approx.							
Barium-orthoclase,	$Or_{19}Ce_1$ 1.5201	1.5240	1.5257	0.010	71° 22′	—	—	Strandmark
"	$Or_{10}Ce_1$ —	—	1.5335	—	—	—	—	Baumhauer
Hyalophane,	Or_4Ce_1 —	—	—	—	75°.5	—	—	Strandmark
"	Or_4Ce_1+ 1.5373	1.5395	1.5416	0.005	74°	—	—	"
"	Or_3Ce_1 —	—	1.5426		77°	—	—	"
"	Or_7Ce_2 1.5419	1.5419	1.5469	0.004	78°.5	—	—	"
Celsian,	Ce 1.5837	1.5886	1.5940	0.006	93° 38′	—	—	"

Optical Orientation.—Albite-anorthite.—Owing to the fact that the angle between the optic axes is large and varies in the neigh-

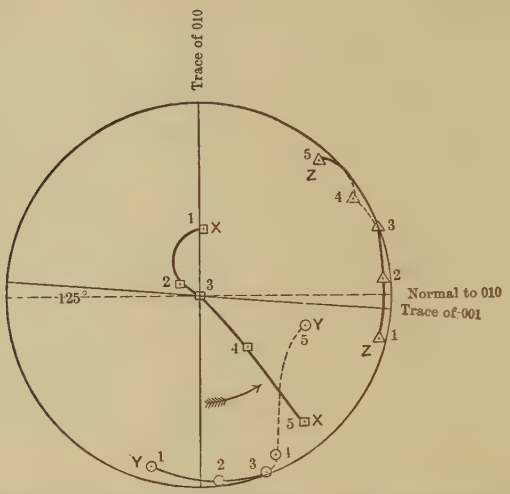


FIG. 30.—Projection of the principal axes of the refraction ellipsoids on a plane perpendicular to (001) (010). 1, albite; 2, oligoclase; 3, andesine; 4, labradorite; 5, anorthite.

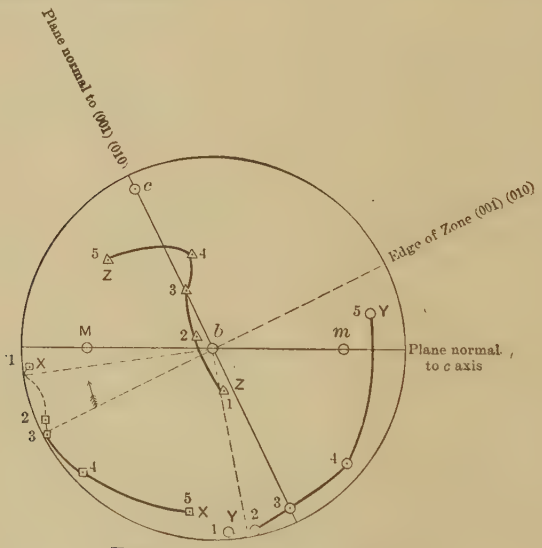


FIG. 31.—Projection on *b* (010).

borhood of 90° it happens that the bisectrix X is the acute bisectrix in some varieties of these feldspars and the obtuse bisectrix in others. Thus albite is optically positive with Z the acute bisectrix and $\rho < v$;

certain oligoclases are optically negative, with Z the obtuse bisectrix and $\rho < v$; labradorite is optically positive, with Z the acute bisectrix and $\rho > v$; anorthite is optically negative, with Z the obtuse bisectrix and $\rho > v$.

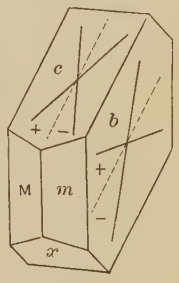


FIG. 32.

The position of the bisectrices and optical normal with respect to the crystal form of the feldspars shifts with the chemical composition. In the albite-anorthite series the bisectrix Z, the direction of vibration of the slowest ray, shifts nearly in a plane perpendicular to the crystal axis a, the plane of the optic axes twisting from a nearly horizontal position in oligoclase to a nearly vertical position in anorthite. This is shown in the spherical projection on the plane perpendicular to crystal axis a, Fig. 30, and in that on the plane (010), Fig. 31. From this it follows that the directions of vibration in cleavage plates parallel to (001) and (010) vary with the composition of the feldspars in a regular manner.

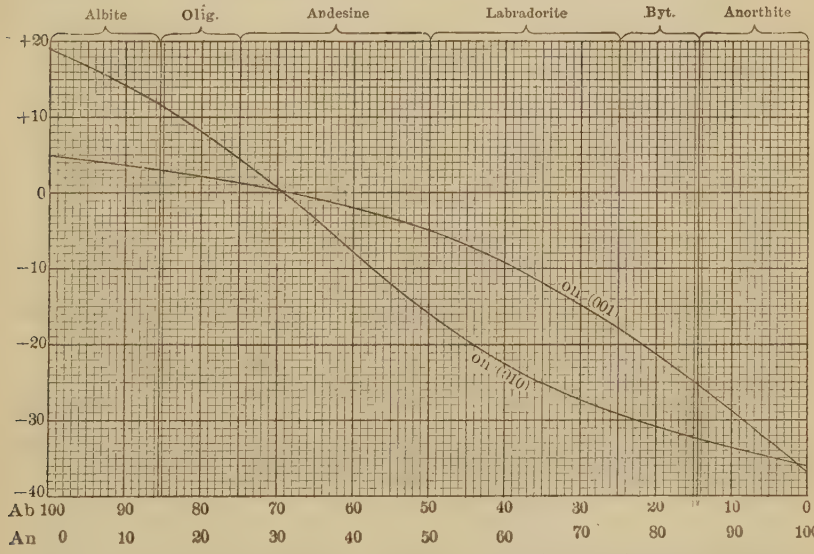


FIG. 33.—Extinction Angles on (001) and (010) in the Lime-soda-feldspars.

(1) Owing to the easy possibility of obtaining definitely oriented crystal sections in these positions the optical orientation of the feldspars in these planes becomes an important means of identification. The angle of extinction measured with reference to the trace of the other cleavage in each cleavage plate is plus or minus according

to the direction in which it is measured from these cleavage cracks, that is, the edge (001) (010). These directions are shown in Fig. 32.

The range of extinction angles on each of the planes (001) and (010) is shown in Fig. 33, constructed from data calculated by Max. Schuster, in which the abscissas correspond to the kinds of feldspar, and the ordinates to the extinction angles. It is to be noted

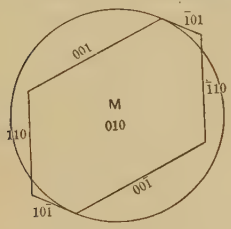


Fig. 34.

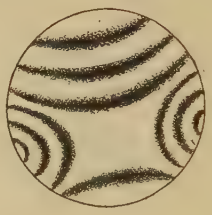


Fig. 35.

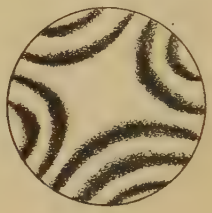


Fig. 36.

Fig. 37.

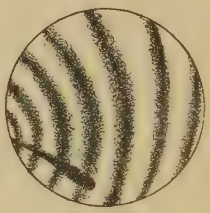


Fig. 38.

Fig. 39.

that for an andesine of about Ab_7An_3 the extinction is zero on both cleavage planes. In this feldspar the bisectrix X is parallel to the crystal axis a. For more sodic feldspars, albite and oligoclase, the extinction angles in both planes are plus; for more calcic feldspars, andesine to anorthite, the extinction angles in both cases are minus, ranging from 0° to −37°.

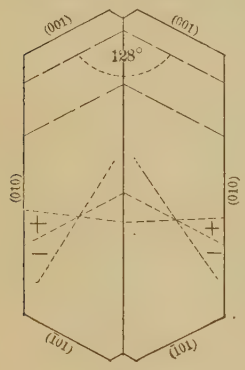


Fig. 40.

The appearance of the interference figures in sections parallel to the second pinacoid (010) for different kinds of lime-soda-feldspars, when the section is oriented as in Fig. 34, is shown in a general manner by Figs. 35 (albite), 36 (oligoclase), 37 (labradorite), 38 (bytownite), 39 (anorthite).

(2) Carlsbad twins of the lime-soda-feldspars cut parallel to the second pinacoid (010) sometimes exhibit both parts of the twinned crystal owing to the composition surface not being parallel in all places to (010). The section may appear as in Fig. 40, in which case the basal cleavage cracks in the twinned parts

make an angle of about 128° with each other. This and the absence of twinning lamellæ following the albite law serve to identify the crystallographic position of the section. Pericline lamellæ may be present. In such sections the extinction angle measured from the trace of the basal cleavage whose range is shown in Fig. 33 serves to determine the kind of lime-soda-feldspar. When zonal structure is present it is commonly most pronounced in sections parallel to (010) and the particular composition of each zone may be determined in the manner just described.

(3) The twinning of feldspars produces symmetrical optical orientations of the twinned parts with respect to the twinning plane. Thus in the commonly occurring twins according to the albite law—twinning and composition plane (010)—any section cut perpendicular to (010) presents two or more twinned parts having like extinction angles measured in opposite directions from the trace of (010), the line separating the twinned lamellæ. These symmetrical extinction angles vary with the crystallographic position of the cutting plane perpendicular to (010), in each kind of feldspar ranging from 0° to a maximum which is characteristic of the kind of feldspar. The range of extinction angles for a number of different members of the albite-anorthite series is shown in the diagrams prepared by Michel-Lévy, with which have been interpolated others obtained from the first by graphical methods, and which therefore have an approximate value (Fig. 41).

In the diagrams the abscissas represent angular positions of the section planes measured from the edge (100) (010); the ordinates are the values of the extinction angles measured from the trace of (010) on the section—the edge of the twinned lamellæ. The heavy curve in each diagram represents the range of extinction angles for a particular feldspar, in passing from a vertical position of the section plane through the acute angle β between the crystal axes c and a.

When a feldspar is twinned only according to the albite law it is possible to judge of its composition from its symmetrical extinction angles only when these approach a maximum. It is necessary to observe as many sections as possible perpendicular to the twinning plane in order to discover the maximum extinction angle. Small angles may occur in all kinds of feldspar. Moreover since the plus or minus sign of the angle cannot be determined in thin sections the maxima of albite and andesine cannot be distinguished by this method alone. But an observation on the index of refraction by the Becke method will distinguish one from the other.

(4) It frequently happens that feldspars twinned according to the

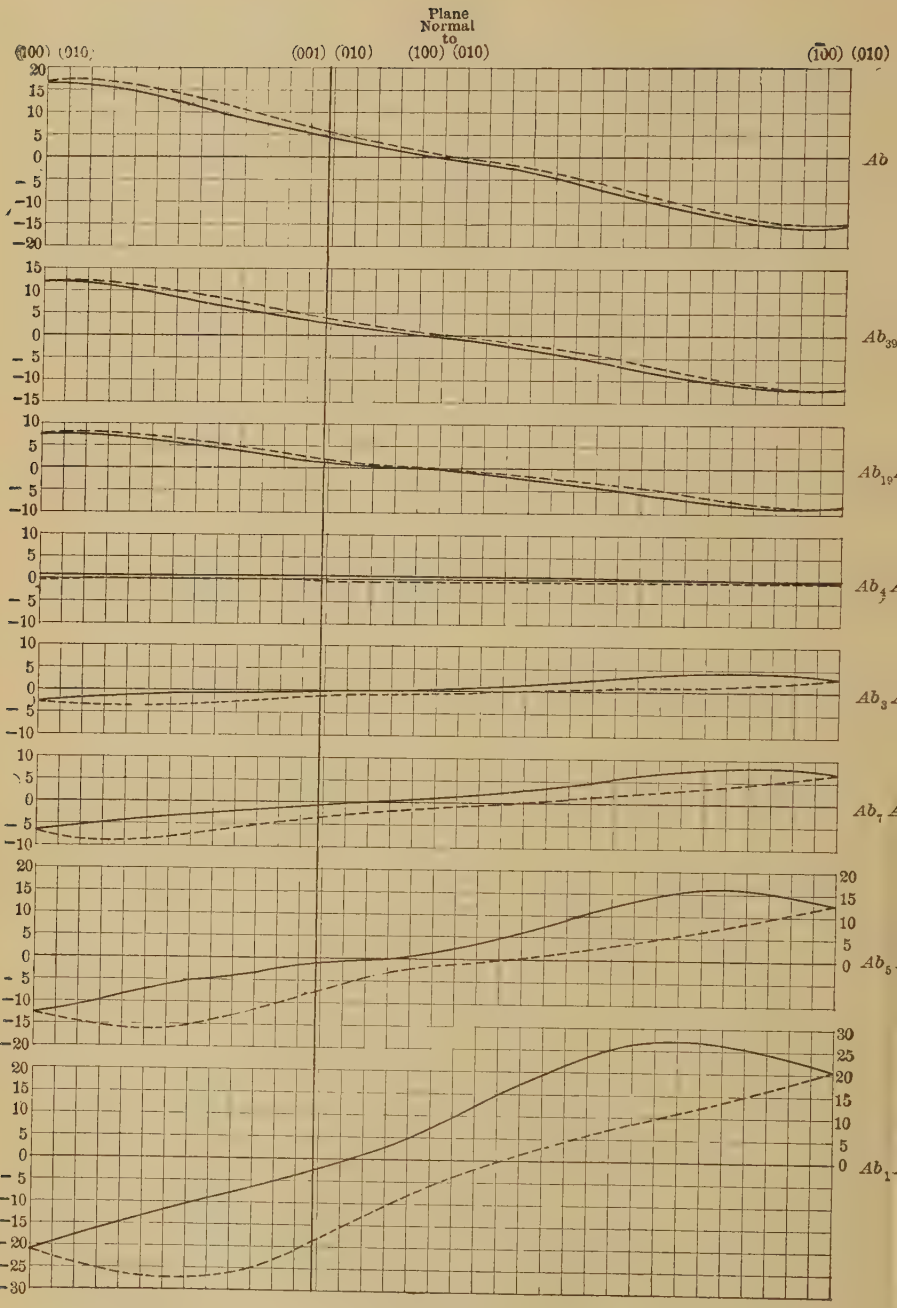
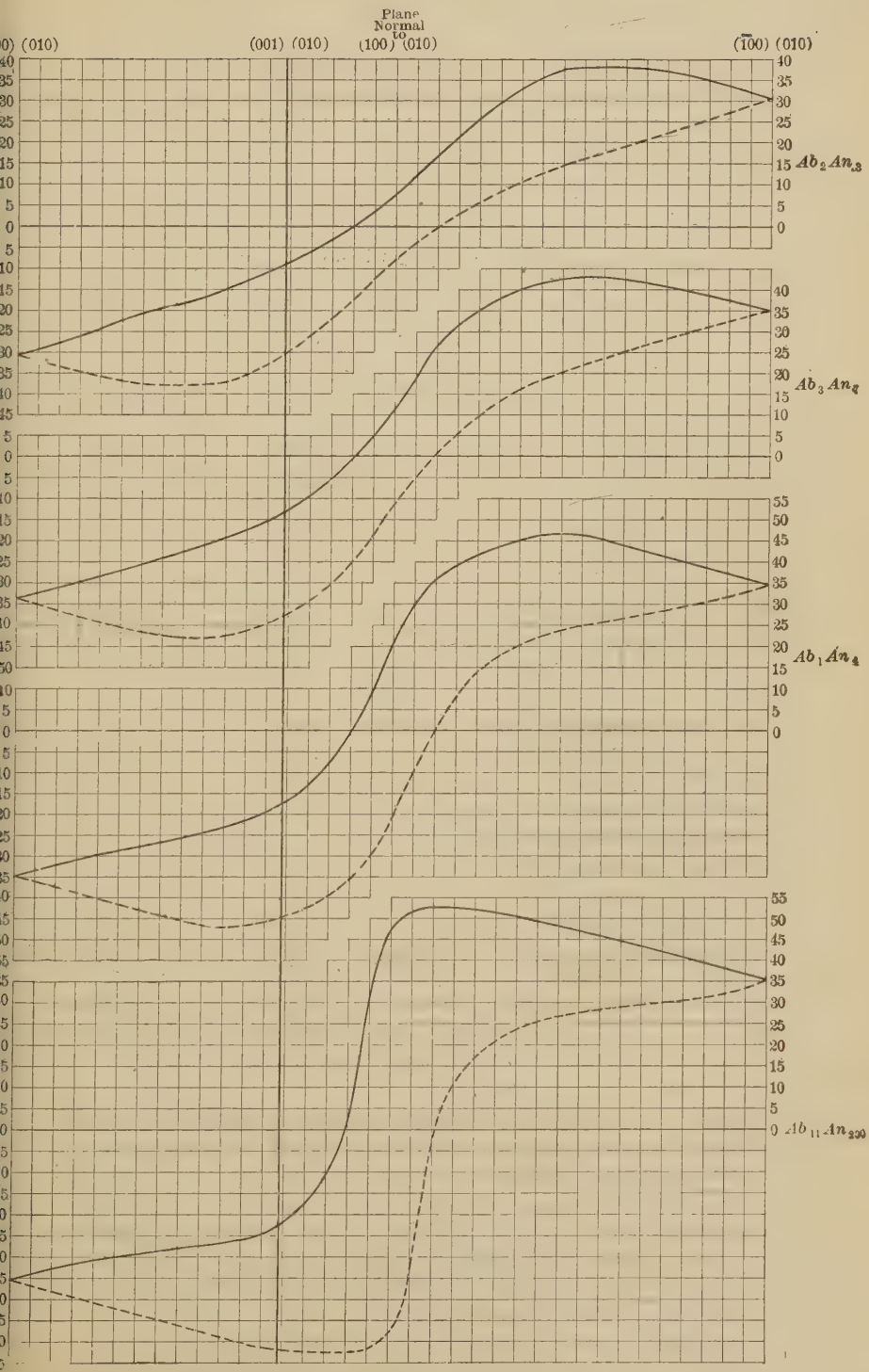


FIG. 41.—Extinction Angles in the Zone no



010) in Carlsbad Twins of Lime-soda-feldspars.

albite law are also Carlsbad twins. In this case a section perpendicular to (010) in one half the Carlsbad twin is also perpendicular to it in the other, so that both sets of lamellæ furnish symmetrical extinction angles (Fig. 42). But the crystallographic position of the cutting plane is not the same in both halves of the Carlsbad twin. In passing from the c axis through the acute angle, β, in one half of the crystal the sections pass through the obtuse angle, $180°-\beta$, in the other half. That is, the curves of extinction angles are reversed for the two parts of the Carlsbad twin. In the diagrams Fig. 41 the second curve is a broken line. It follows from this that for every value of extinction angles in one part of the twin there is a certain extinction angle in the other part, and these pairs are characteristic of different kinds of feldspars with certain exceptions. Thus it will be noticed that all curves pass through zero at nearly the same crystallographic position of the section plane. In each feldspar the same combination of pairs of extinction angles occurs twice, at equal angles on either side the vertical axis, (100) (010)—the twinning axis of the Carlsbad twin.

Fig. 42.

It is also to be noted that in albite the two curves lie close together, while in the more calcic feldspars they are farther and farther apart. This shows that the Carlsbad pairs of extinction angles are nearly alike in albite in all positions of the section, but are different from one another in most positions of the section in more calcic feldspars. This character is easily recognized with crossed nicols by the difference between interference colors in the lamellæ of the two parts of the Carlsbad twin.

Owing to the importance of sections in these positions for the determination of the lime-soda-feldspars ready means for their identification will be pointed out. Sections cut perpendicular to the twinning plane (010) of albite lamellæ may be recognized by the sharpness of the boundary lines between the lamellæ, for they stand normal to the section and do not overlap one another as they would if inclined to it.

Moreover when the lamellæ lie parallel to the cross hairs of the microscope –the directions of vibration in the nicols—adjacent lamellæ are exactly the same color or shade; for, the angles of extinction being symmetrical with respect to the plane of the lamellæ (010), each lamella is turned at the same angle from the position of darkness and has the same double refraction. When the feldspar is also a Carlsbad twin the equally colored albite lamellæ in each part of the Carlsbad twin have distinctive colors, which are nearly the same in albite and oligoclase, but generally different in the more calcic feldspars. The more calcic the feldspar the greater the possible difference between the colors of the two parts. But the diagrams show that in sections parallel to (100) (010) in all feldspars both parts of Carlsbad twins are alike. When the albite lamellæ lie parallel to the cross hairs of the microscope the boundary lines between them are visible though the lamellæ are one color, but when they are turned 45° to the cross hairs the boundary lines disappear altogether, and the contrast between the parts of the Carlsbad twin is generally pronounced when the feldspar is calcic.

(5) Sections of lime-soda-feldspar at right angles to the planes (001) and (010) may be used in determining the kind of feldspar by reason of the characteristic extinction angles, which vary noticeably with the chemical composition of the feldspar.[1] Such sections are commonly nearly rectangular or square, or nearly so, being in fact rhombic with the acute angle about 86°. They are recognized also by the fact that the twinning lamellæ parallel to (010), albite law, and the cleavage cracks parallel to (001) are both normal to the section, which may be determined by observing the behavior of these plane surfaces upon changing the focus of the microscope. For when normal to the section their image does not shift, while the position of the objective changes. Owing to the slight change in the extinction angles in most kinds of feldspar in the neighborhood of this position in the zone normal to (010), as shown in the diagrams of extinction angles Fig. 41, a slight variation of the section plane from an exactly normal position does not affect the application of the method, except in the case of the more calcic feldspars in which the extinction angles vary rapidly with the position in this zone near a plane normal to (001) (010), as shown in Fig. 41.

The variation in the extinction angles for different kinds of feldspars measured from the trace of (010), the twinning lamellæ when

[1] Becker, G. F. 8th Ann. Rept. U. S. Geol. Surv., Part III. Washington, 1898; and F. Becke. Tscher. Min., Petr. Mitth., 18, 1899, p. 556.

present, is shown in the diagram Fig. 43 constructed by Becke from Mallard's formula. The spots located near it correspond to data from Michel-Lévy's article on the determination of the feldspars already cited. As suggested by Becke it appears that the composition of the oligoclases given by Lévy as $Ab_{82}An_{18}$ and $Ab_{72}An_{28}$ may be nearer $Ab_{80}An_{20}$ and $Ab_{75}An_{25}$ respectively. From the diagram it is seen that for most of the lime-soda-feldspars the change in extinction angle

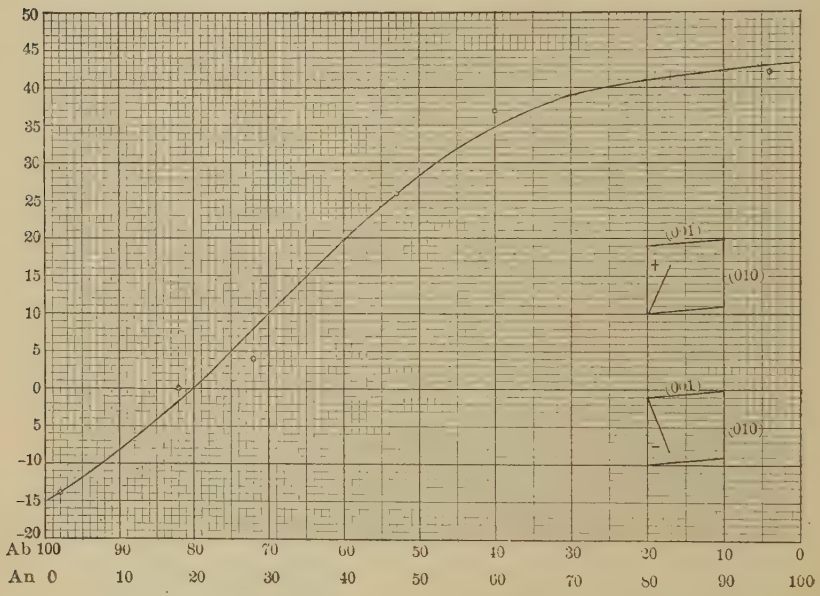


FIG. 43.—Extinction Angles in Sections normal to (001) (010) in Lime-soda-feldspars.

is marked and is nearly 1° for 1 per cent change in albite or anorthite in the more sodic feldspars. In labradorite it is 1° for 2 per cent change in albite molecules, while in bytownite and anorthite it is much less.

The variations in extinction angles in a number of different zones or crystallographic positions have been investigated and described, especially by Michel-Lévy, Fouqué and Becke. The principal cases studied are the following: the zone of (001) (010), which is represented in microscopic prisms of these feldspars;[1] sections perpendicular to the bisectrices X and Z, and also to the optical normal Y; also those at right angles to the optic axes;[2] the determination of the lime-soda-

[1] Lévy and Lacroix, Les Minéraux des Roches, Paris, 1888, p. 201.
[2] Fouqué, Bull. Soc. Min. Fr., 17, 1894, p. 306.

feldspars by means of the interference figures in twins.[1] These and still other methods are described at length by Rosenbusch and Wülfing.[2]

Zonal Structure.—Most sections of lime-soda-feldspar exhibit concentric zones with different optical orientation and different refraction (Fig. 44). The difference in optical orientation appears in the various angles of extinction, or directions of vibration, in the several zones. Ordinarily the innermost feldspar is the most calcic, successive zones becoming more and more sodic. Less frequently there appear alternations of more sodic and more calcic zones. In some cases the difference between adjacent zones is noticeable enough to lead to an abrupt change of interference color or shade in passing from one to the other, and to a recognizable difference in refraction. In some cases there

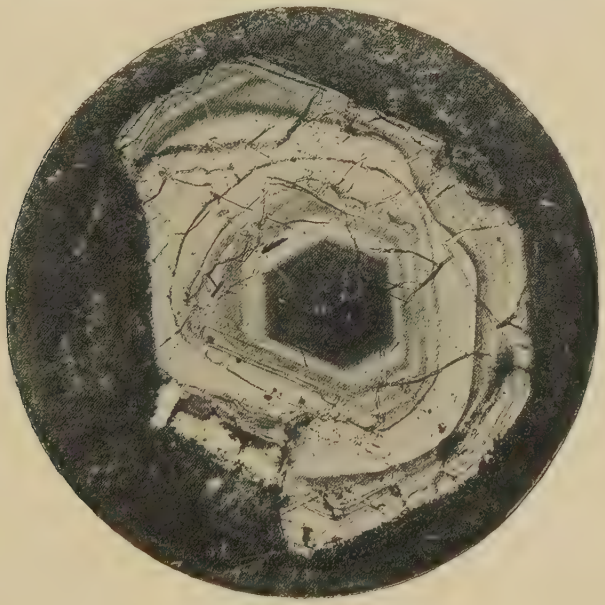


FIG. 44.

is a gradual transition of shade and gradual shifting of optical orientation in passing from the center of the crystal outward.

It is to be observed that the range of variation is much less noticeable in sections perpendicular to albite lamellæ, or to (010), than in those cut parallel to (010). That is to say, feldspar sections which

[1] Becke, Tschr. Min., Petr. Mitth., 14, 1894, pp. 375 and 415; also 16, 1897, p. 180.

[2] Mikroskopische Physiographie, etc., Stuttgart, 1905, p. 345 et seq.

show well-marked albite lamellæ usually exhibit slight zonal structure, while those sections almost free from twinned lamellæ usually exhibit pronounced zonal structure. The reason for this will appear upon a study of the diagrams, Figs. 33 and 41. From the diagrams of extinction angles in sections cut perpendicular to (010), Fig. 41, it appears that there are many positions of section planes where the difference in extinction angles for the various lime-soda-feldspars is only a few degrees, especially within the range from labradorite to oligoclase, whereas Fig. 31, p. 220, shows that in sections parallel to (010) the direction of vibration of the fastest ray, X, shifts almost 90° from albite to anorthite. Within the range of chemical composition frequently met with in these feldspars the variation in optical orientation is more than twice as great in sections parallel to (010) than in many sections cut perpendicular to (010). In general the composition of the outer zone is not more sodic than oligoclase.

It is evident that the apparent relative magnitude of the zones depends on the position of the section in the crystal, whether it passes through the center and in what direction, or whether it cuts only the outer portion of a crystal.

Microcline.— The optical orientation of microcline is described by saying that the plane of the optic axes is nearly perpendicular to

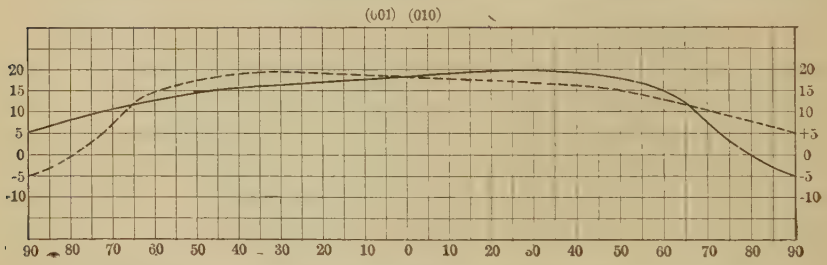


Fig. 45.—Extinction Angles in Zone normal to (010) in Carlsbad Twins of Microcline.

(010) with the acute bisectrix, X, near the direction of the crystal axis a. The angle $2V = 83°$ (Des Cloizeaux), $\rho > r$. On cleavage plates parallel to (001) the extinction angle is $+15°$ or 16°, and on the plane (010) it is $+5°$, each read from the trace of the other cleavage. In sections perpendicular to (010) the symmetrical extinction angles in the albite lamellæ reach a maximum of about 19°. As shown in the diagram Fig. 45, the extinction angles remain between 15° and 19° for sections through 110° of rotation of the cutting plane. Moreover the extinction angles in the second part of a Carlsbad twin are within

5° of those in the first part for sections through nearly 140° of rotation of the cutting plane. For this reason the presence of Carlsbad twins of microcline may easily be overlooked in thin sections.

The minuteness of the twinned lamellæ often prevents a correct determination of the extinction angle, the lamellæ overlapping one another (Fig. 23, p. 210). As the lamellæ become extremely minute their optical effects are blended, and in some cases they are recognized only in the thinnest possible sections. Beyond this their presence is indicated by almost submicroscopic lines of light and shade. Actually submicroscopic lamellar twinning is certainly conceivable and no doubt exists in potash-feldspar. In such a case the plane of twinning (010), which is a plane of symmetry for the twinned parts, becomes apparently a plane of symmetry for the molecules of the feldspar, and the crystal appears to be monosymmetric. This is believed to be the explanation of the apparent monosymmetry of orthoclase. It explains the correspondence between specific gravity, refraction, and other physical properties of the microcline and orthoclase. Orthoclase would then be an example of polysymmetry.

Orthoclase.—The optical orientation of orthoclase varies in different occurrences, which agree, however, in having the acute bisectrix X at an angle of $+5°$ with the crystal axis a in the plane of symmetry (010). They differ in the position of the plane of the optic axes and in the value of the angle between the optic axes. In the great majority of cases the plane of the optic axes is perpendicular to (010), as in Fig. 46,

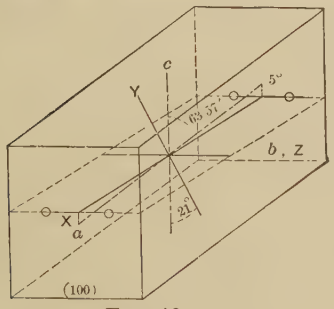


Fig. 46.

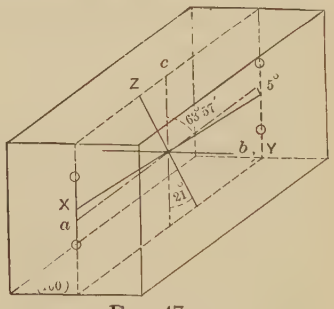


Fig. 47.

and the optic normal is inclined 21° to the crystal axis c. In other cases the plane of the optic axes is parallel to (010), Fig. 47. In the first case $\rho > v$, in the second $\rho < v$. The angle between the optic axes is variable. It has been measured in two cases as follows:

$2V_y = 69° 43'$ and $69° 1'$ in adular, St. Gothard (Des Cloizeaux).

$2V_b = 11° 51'$, $2V_r = 13° 34'$ } in sanidine, Wehr, at 18° C. (Des Cloizeaux).

In certain sanidines it approaches zero, and the crystals appear almost uniaxial. The angle varies noticeably with changes of temperature.

With increasing percentage of soda in the feldspar the angle of inclination of the negative bisectrix X to the crystal axis a increases from $+5°$ to as much as $+10°$. For this reason sections parallel to (010) are important in determining the character of soda-potash-feldspars. They are recognized by being at right angles to the positive obtuse bisectrix Z, or to the optical normal Y, and also at right angles to the basal cleavage, from which the extinction angle may be measured.

Those apparently monosymmetric feldspars with notable amount of soda may be called soda-orthoclase. It has been found that the soda in these crystals does not equal the potash molecularly. When the soda equals or exceeds the potash the crystals exhibit triclinic symmetry and are soda-microcline.

Soda-microcline (anorthoclase). — In potash-soda-feldspars rich in soda there is extremely minute to almost submicroscopic multiple twinning as in microcline. But the lamellæ are generally more minute and in some cases are only recognizable in extremely thin section. In fact the presence of extremely minute microcline twinning is an indication of abundant soda in potash-feldspar.

Extinction on (001) $+5° 45'$ to $+1° 30'$, on (010) $6°$ to $9° 48'$. Acute bisectrix X, $2E_y = 71° 40'$ and $88° 27'$, $\rho > v$, plane of the optic axis perpendicular to (010) approximately. In some of these feldspars there is a small amount of lime, but as they are often perthitically intergrown with lime-soda-feldspar it is not always certain in what way the lime occurs. Lime-soda-microcline (anorthoclase) or *potash-oligoclase* occurs in several localities in such form that it appears that the lime is part of the potash-soda-feldspar. The composition is more nearly that of oligoclase with part of the soda replaced by potash. The multiple twinning is so minute that it is scarcely noticeable in some sections, especially on (001). In such cases the extinction is parallel to the trace of (010) and the crystal appears monosymmetric, like orthoclase. The crystal habit is that of rhombic prisms (110) and $(1\bar{1}0)$, as in rhombenporphyry and certain syenites in Norway, also in lava of Kilimanjaro, Africa. In these feldspars the percentage of lime ranges from 3 to 5 per cent. approximately.

In potash-oligoclase of Tyveholmen, Norway, the extinction angle on (001) in some cases is $1°$ to $2°$; that on (010) is $5\frac{1}{2}°$ to $6°$.

In potash-oligoclase-albite of Kilimanjaro, Africa, the extinction

angle on (001) is 0° in some cases, while in other cases symmetrical extinction angles in sections perpendicular to (010) reach 8° to 11°. Extinction on (010) is 4° 20′ in one case. Acute bisectrix X, $2E=102°$, $2V=60°\ 44'$, $\beta_y=1.5373$. Two feldspars analyzed gave $Or_{1.88}Ab_{4.22}An_1$ and $Or_{2.1}Ab_4An_1$, $(Ab,Or)_{6.1}An_1$, approximately oligoclase.

Hyalophane-celsian.—The potassium-barium-feldspars are monoclinic in all discernible physical properties. The plane of the optic axes is parallel to (010) in celsian, and normal to it in hyalophane.

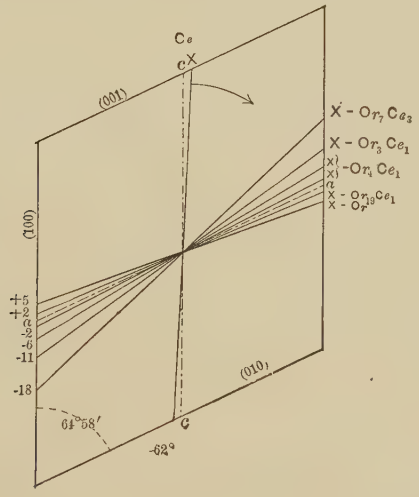


FIG. 48.

The bisectrix X remains in the plane of symmetry with changing composition of the crystals in this series from celsian to orthoclase. Its variation in position is shown in Fig. 48 and is as follows:

		$X \wedge a$	Sp.gr.	
Barium-orthoclase	$Or_{19}Ce_1$....	+ 2°	2.593	Strandmark
	$Or_{10}Ce_1$....	+ 5°	2.645	Baumhauer
Hyalophane	Or_4Ce_1....	− 2°	2.725	Strandmark
	Or_4Ce_1+...	− 6°	2.733	"
	Or_3Ce_1....	−11°	2.756	"
	Or_7Ce_3....	−18°	2.818	"
Celsian	Ce....	−62°	3.384	"

X is the obtuse bisectrix of an optic angle, $-2V=94°$ approx., in celsian, which is therefore optically positive, with $2V=86°$. It is the acute bisectrix of an angle, $2V=74°$–$78°$, in hyalophane, which is optically negative. Crystals of hyalophane are sometimes zonally built with the central portion richer in barium; the outer zones richer in potassium.

Color.—Feldspars when pure are transparent and colorless, and thin sections are colorless. But various inclusions act as pigments, sometimes so dilute as to escape detection under the microscope, often recognizable as bodies of various kinds and sizes. The opaqueness of feldspar crystals arises from multitudes of inclusions. White feldspars may be of any composition, but the more frequent ones are albite. Yellowish, pinkish, and red tints come from iron oxides in most cases. Pink feldspars are very frequently potash-feldspars, but may be albite. Green colors in some cases arise from inclusions of ferrous silicates, such as chlorite; in others their source is not definitely known. Blue opalescence varying from pale to dark shades, and accompanied by other iridescent colors, such as the well-known colors exhibited by labradorite from Labrador, is also exhibited by other kinds of feldspars, oligoclase, albite, soda-microcline, and orthoclase. It has been referred to different causes in different cases. In some it is due to interference of light reflected from extremely minute lamellæ having different refraction from that of the crystal. These lamellæ are usually too minute to be recognized with the microscope. They are approximately parallel to a steep pinacoid of the second kind ($\bar{8}01$), and may be interlaminated feldspar of a different composition from the mass of the crystal in perthitic intergrowth. In some cases there are visible planes of parting in about this direction, when the color is pearly white. In other instances the colors are interference phenomena and reflections from minute inclusions of thin plates, rods, and points, arranged in definite positions in the feldspar crystals, as in labradorite. In sunstone, oligoclase, there are rather large but very thin plates of hematite or a hydrous oxide of iron.

Dark-gray colors are produced by innumerable inclusions of dark-colored minerals in minute particles. These are especially common in the more calcic feldspars, but also occur in some highly alkalic feldspars, as in the soda-microcline of Fredricksvärn.

Inclusions and Intergrowths.—Gas inclusions and liquid inclusions are rarely seen in sections of feldspar, though they occur sparingly. This is in contrast to their common occurrence in quartz.

Glass inclusions are present in feldspars in some lavas, especially in glassy rocks, when they may be very abundant. Occasionally the glass contains one or more bubbles, as many as nine having been observed in one glass inclusion. In general, however, glass inclusions are much rarer in feldspar than in the quartzes in the same rock. Transparent rectangular inclusions oriented parallel to certain directions in crystals of lime-soda-feldspar with lower refraction than the

matrix have been considered to be glass by some petrographers. In certain cases they may be glass, but in others they may be crystals, possibly feldspar.

Inclusions of groundmass occur in the same manner as those of glass, often in such amount that the feldspar forms little more than a network about the inclusions.

Mineral crystals of all kinds may be inclosed in feldspars. When primary they are earlier crystallizations and the feldspar is the later, as is often the case with the alkalic feldspars. When the inclosed mineral is secondary it has been crystallized within the feldspar by replacement or alteration. These inclusions may be of any size relative to that of the feldspar. They may be sparsely scattered or in clouds of great numbers. In some cases the inclusions are grouped, either at the center, the margin, or in concentric shells, producing zones in cross sections.

When the inclusions are numerous and of notable size as compared with that of the inclosing feldspar this is said to be poikilitic. Orthoclase is more often poikilitic than the lime-soda-feldspars, as it frequently is the last mineral to crystallize in a rock, and, if in sufficient quantity and in large crystals, acts as a matrix for other minerals, which is a common occurrence in monzonites.

While feldspar may inclose any of the primary minerals of earlier crystallization in the rock, there are some kinds of inclusions that are characteristic of the feldspars in certain kinds of rocks. That is, they characterize feldspars crystallizing from certain solutions. In some cases these inclusions are in the nature of intergrowths of two minerals.

Graphic Intergrowth.—Quartz inclusions abound in alkalic feldspars, especially potash-feldspars. Usually the two are intergrown in such a manner that irregularly shaped rods of quartz lie in a feldspar matrix, the quartzes having one optical and crystallographic orientation throughout some distance. This is called graphic intergrowth (Fig. 49). It is occasionally observed in striated lime-soda-feldspar of the albite-oligoclase part of the series.

Nephelite occasionally is intergrown with alkalic feldspar in the manner common with quartz, that is, graphically. A similar intergrowth between lime-soda-feldspar and orthorhombic pyroxene has been noted in an andesitic lava.

Perthite.—Feldspar inclusions in feldspar are very common. They occur in several ways. Albite in irregularly lenticular layers traverses potash-feldspar in planes parallel to $(\bar{8}01)$ or (100). Both

feldspars have (010) in common and are otherwise approximately parallelly oriented. This is perthitic intergrowth (Fig 50). It may be megascopic or microscopic. The layers of albite may be almost

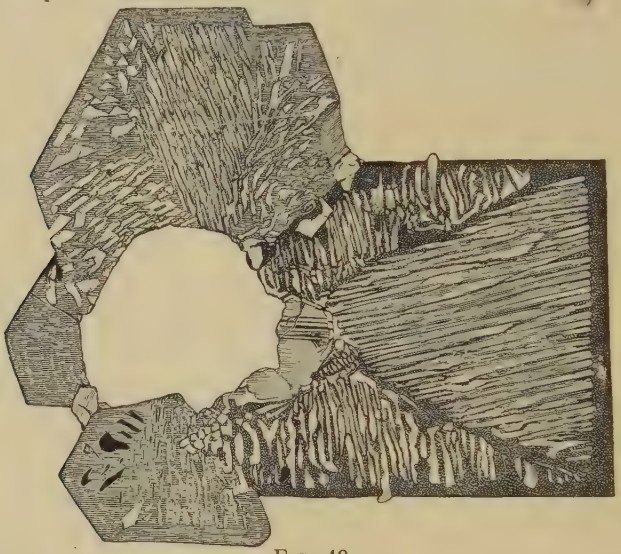


Fig. 49.

microscopic when it becomes cryptoperthite. It occurs with orthoclase and also with microcline.

Parallel growths of one feldspar about another are common. The

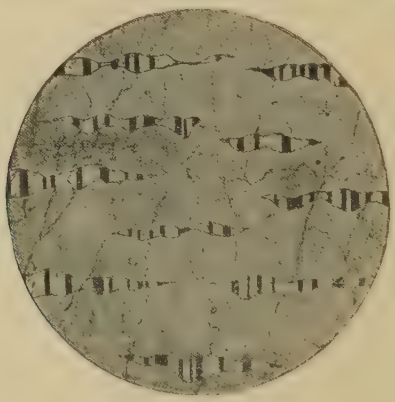


Fig. 50.

zonal structure of many lime-soda-feldspars is of this sort. The feldspars are in concentric shells, crystallographically parallel. Usually the central part is the more calcic. Cases in which the outer

shell is potash-feldspar are common. The central lime-soda-feldspar may be labradorite. In rare instances potash-feldspar is surrounded by lime-soda-feldspar, oligoclase, as in the rapakiwi of Finland.

Clouds of minute dots, rods, and plates of yellow to brown minerals characterize many occurrences of feldspar in the more ferromagnesian rocks, and in those associated with them,—anorthosites. These rods and plates are generally oriented in several directions in the feldspar. and give it a dark color and sometimes a schiller, or opalescence, The inclusions are in some cases titaniferous iron oxide, (?) ilmenite, but may also be in part ferromagnesian silicate, (?) pyroxene.

Clouds of colorless flakes of muscovite or kaolin which render the feldspar white by incident light are common forms of decomposition in orthoclase and albite. The more calcic feldspars when decomposed are replaced in some cases by albite and zoisite (saussurite), by epidote or chlorite together with calcite and quartz in other cases.

Modes of Occurrence.—Lime-soda- and potash-feldspars are the most abundant mineral constituents of the majority of igneous rocks; are abundant in many metamorphic rocks, and are less often present in sedimentary rocks.

In igneous rocks they form phenocrysts in many porphyries with other minerals, and also constitute a large part of the groundmass in most cases. Unstriated orthoclase occurs in coarsely crystalline granites and syenites, and to a less extent in rocks rich in lime-soda-feldspar. It may be accompanied by striated microcline, or the latter alone may be present. The same is true in some porphyries, but potash-microcline is not known in recent unaltered lavas, in which the orthoclase is glassy, and is often called sanidine. The potash-feldspar of metamorphic rocks is commonly microcline, and polysynthetic twinning is produced in orthoclase by pressure in some instances.

Lime-soda-feldspars are more abundant in igneous rocks than potash-feldspars, occurring in all possible ways, as phenocrysts and constituents of the groundmass, and in rocks of all textures. They are less common in metamorphic rocks than potash-feldspar, but are very abundant in some of the crystalline schists. In both cases the more sodic varieties are the more common.

In sedimentary rocks fragments of feldspars appear in arkose sandstones and graywackes. But the readiness with which feldspars decompose, especially the more calcic varieties, prevents their being preserved in great quantities like quartz.

Feldspars occur in veins deposited from aqueous solution to some

extent like quartz, but not so commonly as this mineral. The great pegmatite veins rich in feldspar, and considered to be aqueous deposits by some geologists, are probably igneous intrusions which contained slightly more water than ordinary igneous magmas did at the time of their intrusion.

Feldspars are known to be in some cases the products of gaseous exhalations from volcanic vents, where they accompany other silicates and oxides.

Hyalophane occurs in dolomite in the Binnenthal in the Valais, associated with barite, tourmaline, mica, and other minerals. It also occurs with celsian in dolomitic limestone with manganiferous epidote at the manganese mines of Jakobsberg, Sweden. A barium-bearing feldspar intergrown with albite occurs at Blue Hill, Delaware County, Pa.

Resemblances. — Feldspars exhibiting polysynthetic twinning are not to be mistaken for any other rock-making mineral. But unstriated feldspar may resemble closely quartz, nephelite, and cordierite. From quartz it is usually distinguished by its cleavage, its optically biaxial character, and optically negative character when nearly uniaxial, as in some orthoclases. It has different indices of refraction, except in andesine. Feldspars often exhibit partial alteration, quartz shows none. From nephelite it is distinguished by the cleavage, which is hexagonal in nephelite. The unstriated feldspar commonly associated with nephelite is orthoclase, which has a lower refraction. The double refraction of nephelite is lower than that of feldspar, and does not yield an interference cross in very thin sections. Nephelite is uniaxial and negative. Cordierite when colorless is quite like some feldspar, especially when twinned in polysynthetic lamellæ, which happens in metamorphic rocks. Each is biaxial. But cordierite has almost the same refraction and double refraction as quartz, and the cleavage in one direction only is not generally well developed. In rather thick sections it is pleochroic.

Hyalophane and celsian are most like orthoclase, but differ from it in refraction and specific gravity.

Laboratory Production.—Feldspars have been crystallized in the laboratory in a number of different ways. By fusion in open crucibles, that is, by dry fusion, at temperatures between 1532° and 1230°, most of the lime-soda-feldspars except albite have been produced from liquids of their own composition. Albite has not been made to crystallize in this manner, and the same is true of potash-feldspar. The liquids of these feldspars are too viscous as they approach the

crystallizing temperature. In other cases homogeneous crystals of any mixture of Ab and An have been produced by Day,[1] who has established the melting-points of the lime-soda-feldspars, except for the albite-oligoclase end of the series. Allen has determined the specific gravity of the artificially prepared, pure minerals and of their glasses:

	Melting-point. (Day.)	Sp. gr. Crystal. (Allen.)	Sp. gr. Glass. (Allen.)
Ab_0An_1	1532° C.	2.765	2.700
Ab_1An_5	1500°	2.733	2.648
Ab_1An_2	1463°	2.710	2.591
Ab_1An_1	1419°	2.679	2.533
Ab_2An_1	1367°	2.660	2.483
Ab_3An_1	1340°	2.649	2.458
Ab_1An_0	1120	2.605	2.382

Albite and orthoclase have been produced from fluxes of various kinds: tunstic acid (900°–1000°), alkali tunstates and phosphates, alkali fluoride (700°–800°). They have been produced together with quartz in closed tubes in the presence of moisture.

Barium-sodium-feldspars have been prepared by Fouqué and Lévy by slow cooling from a fusion of silica, alumina, sodium carbonate, and baryta in proportions corresponding to those of oligoclase, andesine, and labradorite.

LEUCITE.

Composition: $KAl(SiO_3)_2$.

Isometric at 500°. *Pseudo-isometric* at ordinary temperatures. Form, icositetrahedrons (211).

Twinning: lamellar parallel to (110).

Cleavage: (110) very imperfect. *Fracture:* conchoidal. H. = 5.5–6. Sp.gr. = 2.45–250; 2.464, Goldschmidt.

Optically isotropic in small crystals, and in all crystals at 500°. Weak double refraction in large crystals at ordinary temperatures; optically positive (+), α (ω) = 1.508, γ (ε) = 1.509. (Des Cloizeaux.)

Color: colorless to white and gray. *Luster:* vitreous.

Chemical Composition. — $KAl(SiO_3)_2$ or $K_2O \cdot Al_2O_3 \cdot 4SiO_2$. SiO_2 55.0, Al_2O_3 23.5, K_2O 21.5. A metasilicate of aluminium and potassium, sometimes with very small amounts of sodium when unaltered. Its chemical similarity to potash-feldspar, except for the proportions of the elements, is to be noted. It occurs in igneous rocks

[1] Am. Jour. Sci., Vol. 19, p. 93, 1905, and Carnegie Institution of Washington, Publ. 31. 1905.

with insufficient silica to convert all of the potassium and aluminium into orthoclase after the other mineral molecules have been satisfied.

Alteration.—Leucite is decomposed by hydrochloric acid without gelatinization. By the replacement of potash by soda and the addition of water leucite alters to analcite. This is a common alteration and is sometimes accompanied by the production of a fibrous, doubly refracting, mineral whose character has not been determined but which is probably a zeolite. In other cases leucite changes to an aggregation of potash-feldspar and nephelite, producing pseudomorphs having the form of leucite crystals. These occur in pseudoleucite-syenites and porphyries in Brazil, Arkansas, Montana, and elsewhere. Leucite also alters to potash-feldspar and muscovite, and is known to be replaced by potash-feldspar alone. Further alteration leads to kaolin. It is not a very stable mineral, which probably accounts for its scarcity in ancient rocks. Most of its occurrences are in Tertiary and more recent lavas.

Crystal Habit.—Leucite crystals have forms which are chiefly the icositetrahedron (211), Fig. 1, with occasionally subordinate (100) and (110). Since the mineral is isotropic at 500° and crystallizes in molten magmas at high temperatures, it undoubtedly belongs in the isometric system and the forms are to be so interpreted. It is frequently rounded and in some occurrences is in irregularly bounded equant anhedrons. Cross sections are usually polygonal or rounded. They may be triangular, square, and 8-sided or 9-sided. In size leucites may range from megascopic crystals 2 cm. in diameter to those of microscopic dimensions.

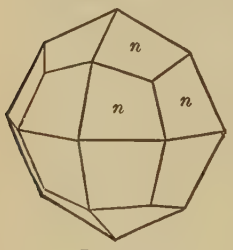


FIG. 1.

In rare instances skeleton forms of leucite have been developed in crystals 0.10 mm. to 0.05 mm. in diameter. The shapes of these imperfect crystals are extremely interesting, as they explain the origin of the characteristic inclusions commonly observed in leucites of various sizes. According to Pirsson [1] there are various stages of growth shown by the leucites in leucitite of Bearpaw Peak, Mont., which are illustrated in Fig. 2. The simplest forms have spurs parallel to the fourfold cubical axes, *a*. In *b* these are thickened at the ends, and in *c* have spread, beginning to define the form of the icositetrahedron. Within this skeleton there is glass base as partial

[1] Pirsson, L. V. Am. Jour. Sci., Vol. II, 1896, p. 145.

inclusions, shown by the dotted areas. In another stage, *d*, there are spurs along the twofold axes. When these reach the margin the form of the icositetrahedron is complete, as in *e*. Further crystallization of leucite leaves club-shaped inclusions, *f*, in place of the triangular ones, there being one radiating from the center toward each face of the icositetrahedron. This is the commoner form of crystal in this rock. Other sections cut in different positions are shown in *g*, *h*, *i*, *j*.

FIG. 2.

The relation of these forms of growth to the distribution of inclusions in leucite will be described in that connection. Similar skeleton forms of leucite occur in lava masses thrown from Vesuvius in 1861.

Twinning. — Leucites generally exhibit lamellar polysynthetic twinning accompanied by weak double refraction. It disappears upon heating crystals to 500°, and is due to molecular rearangement at lower temperatures. Twinning plane (110), repeated parallel to each of the dodecahedral planes. Two cases occur as described by Klein.[1] (1) The main crystal behaves as one individual traversed by subordinate lamellæ parallel to (110). The main crystal is biaxial with a positive acute bisectrix of a small optical angle perpendicular to one of the planes (100), that is, it is parallel to one of the crystal axes. The obtuse bisectrix is parallel to one of the other crystal axes, as though the crystal were orthorhombic. (2) In the second case the leucite consists of three such crystals intersecting each other in such a manner that each of the formerly cubical crystal axes corresponds to an acute bisectrix, and the four crystal faces meeting at the extremities of each cubical axis belong to one orthorhombic individual (Fig. 3). A section through two crystal axes would show four wedge-shaped parts belonging to two individuals. A section parallel to this at some distance from the center would show parts of all three individuals as in Fig. 4. A section perpendicular to one axis near its extremity would cut only one of the parts (Fig. 5). Each is polysynthetically twinned, as indicated by bands in the diagrams. The distribution of the lamellæ is not regular. They are of various lengths and thicknesses.

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[1] Klein, C. Göttinger gelehrte Nachrichten, 1884, No. 11, 421–472; and N. J. Min. Petr. Paleo., 1885, B. B. III, 522–584.

Cleavage, parallel to (110), is generally not noticeable in thin sections of leucite, which are sometimes traversed by irregular cracks. Fracture conchoidal. H. 5.5-6. Sp. gr. = 2.45-2.50; 2.464, Goldschmidt.

Optical Properties.—As already said, leucite is isotropic above 500°, and small crystals in thin section are isotropic at ordinary temperatures. But larger crystals exhibit weak double refraction, $\gamma - \alpha = .001$, which is very faint bluish gray in thin section, and is more easily recognized by its effects on the sensitive tint, purple, of the selenite

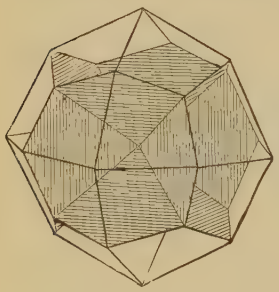

Fig. 3.

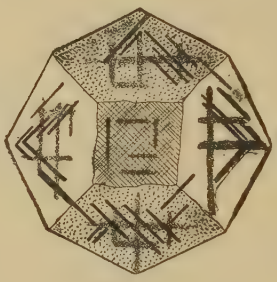

Fig. 4.

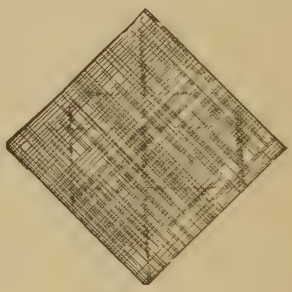

Fig. 5.

plate. The optical behavior has been explained as uniaxial by some, but is considered as biaxial by others. The angle between the optic axes is very small and the acute bisectrix is the direction of vibration of the slowest ray (+). Bisectrices parallel to the crystal axes *a*. α (ω) = 1.508, γ (ε) = 1.509. $\gamma - \alpha = 0.001$. The index of refraction is noticeably lower than that of Canada balsam and orthoclase feldspar.

Color.—Colorless to white or gray in thick crystals, leucite is colorless in thin section.

Inclusions.—Leucites may be entirely free from inclusions or they may contain numerous crystals of other minerals which are usually arranged in very characteristic ways. Sometimes the inclusions are glass and crystals, together with gas; rarely fluid inclusions. The minerals that may be inclosed are those associated with leucite in the rock, and which may have crystallized before it, such as augite, olivine, haüynite, nephelite, melanite, magnetite, picotite, and apatite. The commonest mineral is augite in small prisms.

These inclusions are frequently arranged in a cluster at the center of the leucite, or in one or more concentric zones with prismatic crystals parallel to the surface of the leucite, or they may be in radial lines. The reason for the peculiar radial arrangement is indicated by the

forms of skeleton growth described by Pirsson. The material was probably first shut in as molten magma and afterwards separated into crystals. Concentric arrangements are common to all kinds of crystals, being dependent upon variations in the rate of growth at successive periods in the process of crystallization. Various arrangements of inclusions are shown in Figs. 6 to 11 (Zirkel). Not infre-

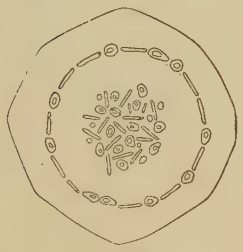

FIG. 6.

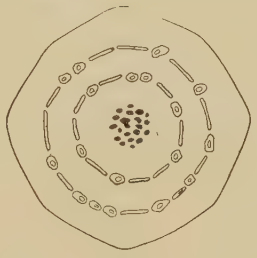

FIG. 7.

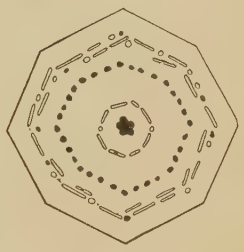

FIG. 8.

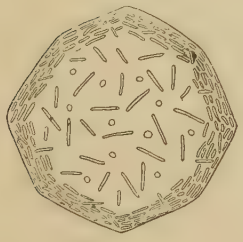

FIG. 9.

FIG. 10.

FIG. 11.

quently these characteristic groups of inclusions call attention to the presence of small leucites which otherwise would escape notice.

In some cases porphyritic leucites are surrounded by a shell of crystals, mostly pyroxene, augite, or ægirite, which are more or less parallel to the surface of the leucite. They appear to have been crowded back by the growth of the leucite crystal.

Resemblances.—In its form in thin section and in its optical properties leucite resembles sodalite and analcite, with both of which it may be associated in rocks. Its refraction is noticeably higher than that of either of these minerals.

Leucite,	$n = 1.508$
Analcite,	$n_y = 1.4874$
Sodalite,	$n_y = 1.4858$

Analcite sometimes exhibits faint double refraction in lamellar bands, which is weaker and not so common as the lamellar twinning

in leucite. Sodalite seldom exhibits faint double refraction, but is frequently clouded with minute inclusions not often seen in leucite.

Modes of Occurrence.—Leucite occurs only in igneous rocks, for the most part in lavas low in silica, both those rich in alumina and alkalies and those rich in ferro-magnesian elements. It occurs in some intrusive porphyries and less often in granular phanerocrystalline rocks resembling fine-grained gabbro, missourite. It forms phenocrysts in some instances, and microscopic constituents of the groundmass in others. It may be euhedral, subhedral, or anhedral; being in the latter form when it was the last constituent in the rock to crystallize, as is the case with orthoclase frequently. In this connection it is interesting to notice its high melting point, not yet definitely determined. It is infusible before the blowpipe.

It is chiefly developed in lavas of Tertiary and more recent age, and is found but rarely in older rocks, where it is usually altered to other minerals, as at Magnet Cove in Arkansas, and in Brazil. In these localities it is probably of Cretaceous age. It has been found in the Silurian in Siberia. Leucite occurs in widely remote localities in all parts of the world.

Laboratory Production.—Leucite has been produced in a number of different ways. Fouqué and Michel-Lévy [1] obtained it by melting together the components of leucite and augite in an open crucible. The result resembled a natural rock. It has been produced by heating silica with an excess of alumina and potassium vanadinate at a red heat [2]; also by heating silicon chloride with potash and alumina.[3]

Leucite has been produced in the presence of water in a closed vessel at about 500° by the reaction of potash and silica on muscovite from Moss, Norway. It has also been obtained from aqueous solution by heating to a dull red heat in a closed vessel silica, alumina, and potash in the proper proportions.[4] In both these cases the crystals are optically and crystallographically uniaxial and negative, with weak double refraction.

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[1] Fouqué, F., and Michel-Lévy, A. Comp. Rend., LXXXVII, 1878, 961. Ibid., XC, 1880, 698. Bull. Soc. Min. Fr., III, 1880, 118.

[2] Hautefeuille. Comp. Rend., XC, 1880, 313 and 378.

[3] Meunier, St. Comp. Rend., XC, 1880, 100.

[4] Friedel, Ch. and G. Bull. Soc. Min. Fr., XIII, 1890, 129 and 182.

SODALITE GROUP.

COMPOSITION: SODALITE, $Na_4(AlCl)Al_2(SiO_4)_3$
HAÜYNITE, $(Na_2,Ca)_2(NaSO_4Al)Al_2(SiO_4)_3$
NOSELITE, $Na_4(NaSO_4Al)Al_2(SiO_4)_3$
LAZURITE, $Na_4(NaS_3Al)Al_2(SiO_4)_3$

ISOMETRIC SYSTEM.

Twinning plane (111) in sodalite and noselite; (210) in haüynite.

Cleavage: dodecahedral, more or less distinct in all but noselite. Fracture conchoidal to uneven. H. = 5.5–6.

Specific gravity: Sodalite. 2.14–2.30
Haüynite. . . . 2 4 –2.5
Noselite. 2.25–2.4
Lazurite. 2 38–2 45

OPTICAL PROPERTIES: isotropic. Index of refraction low:
Sodalite, $n_y = 1.4827$ (Feussner)
Haüynite, $n_y = 1.4961$ (Tchihatchef)

Color: Sodalite—gray, greenish, yellowish, white, blue, lavender-blue, light red.
Haüynite—bright blue, sky-blue, greenish blue, asparagus-green, red, yellow.
Noselite—grayish, bluish, brownish, sometimes black. In thin sections colorless to brown.
Lazurite—Berlin-blue or azure-blue, violet-blue, greenish blue.

Luster: vitreous to greasy.

SODALITE.

Chemical Composition.—$Na_4(AlCl)Al_2(SiO_4)_3$ or $3(NaAlSiO_4) + NaCl = 3(Na_2O \cdot Al_2O_3 \cdot 2SiO_2) + 2NaCl$. SiO_2 37.2, Al_2O_3 31.6, Na_2O 25.6, Cl 7.3 = 101.7, less O 1.7 for Cl = 100. Potassium may replace a small part of the sodium. This is equivalent to a sodium-nephelite plus sodium chloride. The mineral is almost the same chemically as nephelite and plays a somewhat similar rôle in igneous rocks, being commonly associated with nephelite.

Alteration.—Decomposed by hydrochloric acid with separation of gelatinous silica. Soluble even in acetic acid. Sodalite alters readily to radiating aggregations of zeolites, chiefly natrolite accompanied in some instances by hydronephelite, thomsonite, and diaspore (Norway). In other cases it alters to kaolin and muscovite.

Crystal Form.—The rhombic dodecahedron (110) is the dominant form, rarely with subordinate (100), (111), or (211). The crystals are sometimes elongated in the direction of a threefold axis. Cross

sections of euhedral crystals are usually six-sided or four-sided. Subhedral and anhedral forms are more common. The twinning on the octahedral plane is seldom observed in thin section. Euhedral crystals occur as phenocrysts in porphyritic rocks. Anhedral crystals are the usual forms in non-porphyritic phanerocrystalline rocks.

Cleavage parallel to (110) is generally not distinct in thin sections of sodalite within rocks, but in crystals grown in cavities in lava on Mt. Somma it is very distinct.

Fracture cracks are in general not very noticeable.

Optical Properties.—Isotropic in thin section, sometimes with faint double refraction in the vicinity of inclusions. Noticeable for its low refraction, which is less than that of most of the other colorless minerals with which it is associated, and also lower than Canada balsam. $n_y = 1.4827$ on Bolivian sodalite (Feussner). $n_y = 1.4858$ on Vesuvian sodalite (Tchihatchef). Upon diaphragming the light the surface appears rough or shagreened as with muscovite, the refraction of sodalite being as much lower than that of balsam as that of muscovite is higher.

Color.—In thick crystals as already given. In thin section it is generally colorless, but may be blue, greenish, light red, or yellow.

Inclusions.—When in the coarser-grained rocks sodalite often includes the minerals associated with it: iron oxides and small prisms of pyroxene or amphibole. It may also contain abundant fluid inclusions. These are often clustered in the center of the sodalite. When it occurs in porphyritic lavas it is freer from inclusions, which are sometimes glass, rarely fluid.

Modes of Occurrence.—Sodalite occurs in igneous rocks rich in alkalies and low in silica accompanying nephelite or leucite. It is developed in phanerocrystalline rocks and also in aphanitic and glassy lavas. In some cases it is among the earlier crystallizations; in others it is one of the last to crystallize, as in certain syenites. Sodalite also occurs as a secondary mineral in some instances, as an alteration product of nephelite.

Resemblances.—Sodalite is characterized by its low index of refraction, 1.4827, nearly that of tridymite. It resembles the other members of the sodalite group, from which it is difficult to distinguish it except by chemical tests. It is distinguished from leucite by lower refraction and absence of double refraction in most cases. It is easily confused with analcite, which has almost the same index of refraction, 1.4874, but which sometimes exhibits very weak double refraction like

leucite. It has somewhat lower index of refraction than rock glass, which, however, varies with its chemical composition. It may be distinguished from glass by the arrangement of inclusions centrally, or by the exclusion of crystals which occur more abundantly in the surrounding matrix. It is also distinguished from glass by cleavage, when it is present, and by its behavior toward acids.

Laboratory Production.—Sodalite has been obtained by heating powdered nephelite in an excess of sodium chloride, also by heating to 500° muscovite with soda in proportion to form nephelite, with the addition of sodium chloride. The crystals of sodalite formed in the laboratory have the habit of those found in rocks.

HAÜYNITE—NOSELITE.

Chemical Composition.—*Haüynite:* $(Na_2,Ca)_2(NaSO_4Al)Al_2(SiO_4)_3$ or $3[(Na_2,Ca)Al_2(SiO_4)_2] + 2Na_2SO_4 = 3[(Na_2,Ca)O \cdot Al_2O_3 \cdot 2SiO_2] + 2Na_2SO_4$.

Noselite: $Na_4(NaSO_4Al)Al_2(SiO_4)_3$ or $3Na_2Al_2(SiO_4)_2 + 2NaSO_4 = 3[Na_2O \cdot Al_2O_3 \cdot 2SiO_2] + 2Na_2SO_4$.

Haüynite and noselite are parts of an isomorphous series grading from the pure sodic compound to one containing two-thirds as much lime as soda; the pure calcic compound not having been found in rocks up to this time. The sodic end of the series with little or no lime is noselite. The more calcic minerals are haüynite. The two grade into one another chemically, and resemble one another physically to such an extent that they are not easily distinguished from one another in rocks.

When Na_2:Ca::3:2, the composition of haüynite is SiO_2 32.0, SO_3 14.2, Al_2O_3 27.2, CaO 10.0, Na_2O 16.6 = 100. For pure sodium-noselite, SiO_2 31.7, SO_3 14.1, Al_2O_3 26.9, Na_2O 27.3 = 100. A small amount of potassium is present in some cases.

Alteration.—Decomposed by hydrochloric acid with the separation of gelatinous silica. Upon evaporation of the solution from haüynite crystals of gypsum are obtained in abundance. These are scarce or absent in solutions from noselite.

The alteration of haüynite results in most cases in aggregations of needle-like zeolite, often radiating. The zeolite is natrolite, which is sometimes accompanied by other zeolites which are probably stilbite and chabasite. Calcite is also developed in some cases. Weathering leads to a dense kaolin-like aggregation, often colored by limonite.

Crystal Form.—When euhedral the form is the rhombic dodecahedron (110), sections of which are four- or six-sided. More or less rounded and irregularly shaped crystals also occur as phenocrysts. Anhedral forms are common.

Twinning is not noticeable in thin sections.

Cleavage or fracture cracks are seldom noticeable, but are sometimes highly developed and distinct.

Optical Properties.—Isotropic in thin section, occasionally exhibiting weak double refraction similar to that shown in garnet in some instances. There is also double refraction about inclusions and along fracture lines. The index of refraction is low. $n_y = 1.4961$ on blue haüynite from Niedermendig. Slightly higher than that of sodalite, but less than that of leucite.

Color.—In thin section quite varied: colorless, sky-blue, gray, brownish, red, yellow, green. The most frequent colors are light blue and colorless. The color is not always distributed uniformly through the crystal, but is in streaks or spots, or in zones. It is sometimes located on cracks in such a manner as to suggest its secondary character. It is destroyed by heating to a high temperature.

Inclusions.—Haüynite is generally characterized by a great abundance of minute inclusions which are mostly gas and glass inclusions, seldom fluid as in the haüynite of Niedermendig. There are also microlites of an opaque mineral. The glass inclusions when large enough to be seen distinctly often have the crystal shape of the haüynite matrix, rhombic dodecahedron. The microlites are in some cases six-sided plates, or irregularly shaped flakes of hematite or ilmenite, either opaque or translucent, brown, red, or yellow. The minute inclusions may be like a swarm distributed throughout the haüynite, or they may be clustered at the center of the crystal, or on the margin, or they may be in concentric zones of greater or less abundance. Frequently they are in lines or streaks parallel to the threefold axes of the crystal, so that sections cut parallel to (100) are crossed by lines at right angles to one another; those cut parallel to (111) are crossed by lines in three directions at 120° to one another; while other sections are traversed by lines in various directions.

In some instances the tabular microlites are arranged parallel to the cleavage planes (110), and it may be that in such cases they are secondary and have been deposited along the cleavage cracks.

In certain occurrences there are opaque borders which are bluish black or brownish black in incident light. They are quite sharply

defined from the central portion of the crystal and appear to be zones filled with inclusions which have been altered and impregnated with limonite, with which is probably kaolin.

The characteristic inclusions combined with the colors and isotropic property of haüynite and noselite serve as diagnotic features. They are readily distinguished from apatite, which may contain somewhat similar inclusions, by the different indices of refraction, higher and lower than balsam.

Modes of Occurrence.—Haüynite and noselite occur only in igneous rocks and almost wholly in lava forms. In a few instances they have been recognized in coarsely crystalline rocks,—in nepheliteyenite from Montreal (Osann). They generally accompany nephelite or leucite in rocks low in silica and relatively rich in alkalies. They are common in euhedral crystals, megascopic or microscopic, that have crystallized among the first of the salic minerals, usually before nephelite.

Laboratory Production.—These minerals have not yet been produced in the laboratory.

LAZURITE.

Chemical Composition.—Chiefly $Na_4(NaS_3Al)Al_2(SiO_4)_3$, together with haüynite and sodalite molecules in the ratio of 77:16:7. The percentage of the ultramarine molecule as calculated by Brögger is SiO_2 31.7, Al_2O_3 26.9, Na_2O 27.3, S 16.9 = 102.9, deducting (O = S) 2.9 = 100. The mineral lazurite from the vicinity of Lake Baikal, Siberia, was found to have the following composition: SiO_2 32.52, Al_2O_3 27.61, CaO 6.47, Na_2O 19.45, K_2O 0.28, SO_3 10.46, Cl 0.47 = 99.57.

Crystal Form.—Dodecahedrons and sometimes cubes, with imperfect cleavage parallel to (110), in microscopic crystals in a mixture of other minerals called lapis lazuli.

Color.—Various tones of blue; azure, purplish, greenish.

Inclusions.—Lazurite is intimately associated with microscopic crystals of diopside free from iron, a colorless amphibole (koksharovite), muscovite, calcite, pyrite, and in some instances a small amount of scapolite, lime-soda-feldspar, orthoclase, apatite, titanite, zircon, and an undetermined mineral which is optically positive, and is probably uniaxial.

Modes of Occurrence.—Lapis lazuli occurs in limestone in connection with granitic rock in such a manner as to appear to be a result of contact metamorphism.

NEPHELITE GROUP.

COMPOSITION: NEPHELITE $\left(\frac{m}{n} > \frac{3}{1}\right)$, $\begin{cases} m\mathrm{NaAlSiO_4} \\ n\mathrm{KAl(SiO_3)_2} \end{cases}$

SODIUM-NEPHELITE, *artif.*, $\mathrm{NaAlSiO_4}$

KALIOPHILITE, $\mathrm{KAlSiO_4}$

EUCRYPTITE, $\mathrm{LiAlSiO_4}$

HEXAGONAL. (?) PYRAMIDAL. Axis $c = 0.8389$. Nephelite.

Cleavage: distinct parallel to $(10\bar{1}0)$, imperfect parallel to (0001) in nephelite. Perfect parallel to (0001) in kaliophilite; also present in eucryptite.

Fracture: subconchoidal in nephelite. Brittle. H. = 5.5–6 in nephelite, 6 in kaliophilite. Sp. gr. = 2.60–2.65 in nephelite; 2.493–2.602 in kaliophilite; 2.667 in eucryptite.

OPTICAL PROPERTIES: uniaxial, optically negative. Double refraction low; in nephelite $\omega_y = 1.5416$, $\varepsilon_y = 1.5376$. Mte. Somma (Wolff).
$\omega_y = 1.5469$, $\varepsilon_y = 1.5422$. Arkansas (Penfield).
$\omega - \varepsilon = .004$–$.005$.

Color: colorless, white and yellowish, greenish to bluish gray; also browns and reds in nephelite. *Luster:* vitreous to greasy.

NEPHELITE (ELEOLITE).

Chemical Composition.—Nephelite in all cases contains potassium in addition to sodium, but in varying proportions, from one fifth to one third of the sodium molecularly. Pure sodium-nephelite has been made in the laboratory and is orthosilicate of aluminium and sodium, $\mathrm{NaAlSiO_4}$. With the addition of potassium there is a change in the proportion of silica, which is not definitely determinable from the analyses. Doelter has suggested that the potassium is present in a metasilicate molecule similar to that of leucite, $\mathrm{KAl(SiO_3)_2}$, and that the composition of nephelite is expressed by the formula

$$m\mathrm{NaAlSiO_4} \cdot n\mathrm{KAl(SiO_3)_2}. \quad \left(\frac{m}{n} = \frac{5}{1} \text{ to } \frac{3}{1}\right)$$

But this is not strictly correct. An analysis by Harrington of very excellent material in the form of large crystals from Dungannon Township, Ontario, yielded the following: SiO_2 43.51, Al_2O_3 33.78, Fe_2O_3 0.15, MgO trace, CaO 0.16, Na_2O 16.94, K_2O 5.40, ign. 0.40 = 100.34. This corresponds to $\mathrm{Na_{10}K_2Al_{12}Si_{13}O_{50}}$, which is equivalent to $5(\mathrm{Na_2O \cdot Al_2O_3 \cdot 2SiO_2}) + \mathrm{K_2O \cdot Al_2O_3 \cdot 3SiO_2}$. $Na_2O : K_2O :: 5 : 1$.

In pure sodium-nephelite $SiO_2 = 42.3$, $Al_2O_3 = 35.9$, $Na_2O = 21.8$.

Alteration.—Easily attacked by hydrochloric acid with the separation of gelatinous silica. Nephelite alters somewhat readily into a number of different minerals according to circumstances. The most common changes are to sodalite and analcite; also to natrolite, thomsonite, and hydronephelite (ranite). Nephelite is often replaced by aggregates of cancrinite. It alters in other cases to potassium-mica or pinite, also called gieseckite and liebenerite. Finally it may be reduced to kaolin.

Crystal Habit.—When euhedral nephelite crystals are stout hexagonal prims ($10\bar{1}0$), or thick plates, with the basal pinacoid

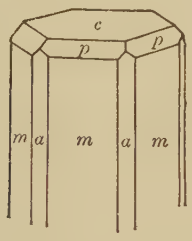

Fig. 1.

Fig. 2.

(0001), seldom with subordinate pyramidal faces ($10\bar{1}1$) and subordinate prism faces of the second kind ($11\bar{2}0$), Fig. 1. The usual cross-sections are hexagons and short rectangles. Euhedral crystals occur as phenocrysts and also as small crystals in fine-grained groundmasses. The pyramidal symmetry is only discovered by etching (Fig. 2) and does not appear in the crystal form. Subhedral and anhedral nephelites are nearly equant, irregularly shaped, crystals without characteristic forms. They are more common in the phanerocrystalline granular rocks.

Cleavage.—Prismatic and basal cleavages are generally developed in thin sections, but are not always noticeable. They become more pronounced when alteration has set in along the cleavage planes.

Fracture lines like the cleavage are not generally noticeable, because of the likeness in refraction between nephelite and Canada balsam.

Optical Properties.—Nephelite is uniaxial and negative (− with low double refraction. $\omega - \varepsilon = 0.004\text{-}0.005$, so that thin sections do not yield an interference figure. The interference colors are bluish gray to white. The optical character may be determined in longitudinal sections of prism: by noting the fast and slow rays, the optic axis lying parallel to the longer diameter of the prism.

In extremely minute crystals the double refraction is scarcely perceptible. The index of refraction is nearly the same as that of quartz and higher than that of Canada balsam and the alkalic feldspars:

Mte. Somma	$\omega_y = 1.5416$	$\varepsilon_y = 1.5376$	(Wolff)
Arkansas	$\omega_y = 1.5427$	$\varepsilon_y = 1.5378$	(Wadsworth)
"	$\omega_y = 1.5469$	$\varepsilon_y = 1.5422$	(Penfield)

Color.—In thick crystals, colorless to white, also gray, greenish and bluish, brown and red. In thin sections colorless. Its luster is usually greasy, but sometimes it is vitreous. It has been customary to call the duller varieties *eleolite*, and the more vitreous *nephelite*. But there seems to be no need for two names for the same mineral, especially when it happens that the luster of very small crystals is not recognizable. Generally the mineral when in coarse-grained rocks has been called eleolite, and when in lavas nephelite. It is better to call it nephelite in all cases.

Inclusions.—Nephelite has no characteristic inclusions by which it may be recognized. It is often quite free from inclusions, but in other cases may abound in them. It may contain any of the minerals associated with it in the rock. Often there are numerous gas and fluid inclusions, sometimes with cubes of NaCl; also glass inclusions when in lavas. Mineral inclusions frequently observed are needles of ægirite and amphibole. They are sometimes green pleochroic chlorite, and in other cases hydrous iron oxide, or hematite, giving brown and red colors to the crystal. Fluorite has also been noted, and the various alteration products already mentioned. The primary inclusions are n some cases scattered, in others in clouds or streaks, in others in zonal arrangement.

Intergrowths of nephelite with alkalic feldspar occur in some nephelite-syenite, like the graphic intergrowth of quartz and feldspar.

Resemblances.—Nephelite in thin section is most like quartz and unstriated feldspar, and somewhat like apatite. It has about the same double refraction as apatite and is optically negative (−), but the index of refraction is noticeably lower, and it lacks the rough surface and relief noticeable on apatite when the light is diaphragmed. It is nearest quartz in refraction, is somewhat lower in double refraction, is negative, does not yield an interference figure in very thin section, generally exhibits cleavage, and often shows more or less alteration not found in quartz. It does not occur in rocks with primary quartz. Unstriated feldspar is usually orthoclase; from this nephelite differs in refraction, being noticeably higher and easily

distinguished from it by diaphragming the light and changing the focus (Becke method). Otherwise the double refraction in the two minerals is quite similar; both show cleavage, one hexagonal in some sections, but rectangular in others, like feldspar. Both may show partial alteration. There can be no confusion with striated feldspars, but unstriated andesine has nearly the same index of refraction, has slightly higher double refraction, and exhibits a biaxial interference figure.

Modes of Occurrence.—Nephelite is a primary constituent of many igneous rocks of all textures. It occurs in certain gneissoid and schistose rocks that appear to be partly metamorphosed igneous rocks. In fact this texture is very highly developed in some nephelite rocks in Russia, Norway, and Canada. While in some cases the schistose texture may be primary, it is undoubtedly secondary in others. It is probable that nephelite has recrystallized during the metamorphism of nephelite-syenites.

Nephelite occurs as a secondary mineral in pseudomorphs with orthoclase after leucite; its ability to crystallize in this way renders it probable that it may recrystallize during the crushing and shearing that produces schistose texture. It is to be noted, however, that nephelite is not found in the crystalline schists except as metamorphosed facies of nephelite-bearing igneous rocks.

Laboratory Production.—Nephelite has been produced in an open crucible by fusing its constituents at a red heat. The fusibility of nephelite is 3.5. It has also been obtained by melting its components in an excess of sodium vanadinate. The characters are those of the natural mineral.

KALIOPHILITE.

Chemical Composition.—Kaliophilite is orthosilicate of aluminium and potassium. $KAlSiO_4$ or $K_2O \cdot Al_2O_3 \cdot 2SiO_2 = SiO_2$ 38.0, Al_2O_3 32.3, K_2O 29.7 = 100, a potassium-nephelite. It is decomposed by hydrochloric acid with gelatinization.

Crystal Form.—Hexagonal needles in bundles and in fine threads. It has perfect basal cleavage.

Optically uniaxial and negative. Colorless, with silky luster. Kaliophilite occurs in ejected blocks at Mte. Somma, that is, as a product of contact metamorphism in limestone, caused by the lava; in some cases in rock composed of augite with mica, in other cases in gray granular calcite with dark-colored augite and yellow melilite. It is not known as a primary constituent of igneous rocks.

It has been produced in the laboratory by digesting nephelite with potassium hydrate.

EUCRYPTITE.

Chemical Composition.—Orthosilicate of aluminium and lithium, $LiAlSiO_4$ or $Li_2O \cdot Al_2O_3 \cdot 2SiO_2 = SiO_2$ 47.6, Al_2O_3 40.5, Li_2O 11.9 = 100, lithium-nephelite. It is decomposed by hydrochloric acid with gelatinization.

It crystallizes in the hexagonal system in irregularly shaped forms graphically intergrown with albite as an alteration product of spodumene in the coarse pegmatite at Branchville, Conn. (Figs. 1 and 2). Its formation with albite from a metasilicate, spodumene,

FIG. 1.

FIG. 2.

is analogous to the formation of nephelite with orthoclase from the metasilicate, leucite.

CANCRINITE.

COMPOSITION: $H_6Na_6Ca(NaCO_3)_2Al_8(SiO_4)_9$.

HEXAGONAL. $c = 0.4224$.

Cleavage: prismatic $(01\bar{1}0)$ perfect; $(11\bar{2}0)$ less so. H. = 5–6. Sp. gr. = 2.42–2.5.

OPTICAL PROPERTIES: uniaxial, negative (−). $\omega_r = 1.5244$, $\varepsilon_r = 1.4955$. $\omega - \varepsilon = 0.0289$.

Color: white, gray, yellow, green, blue, reddish. In thin section colorless. *Luster:* subvitreous, pearly to greasy.

Chemical Composition.—$H_6Na_6Ca(NaCO_3)_2Al_8(SiO_4)_9$, which may be written $3H_2O \cdot 4Na_2O \cdot CaO \cdot 4Al_2O_3 \cdot 9SiO_2 \cdot 2CO_2$. Cancrinite has nearly the same composition as nephelite with the addition of a little lime, carbon dioxide, and water. It is largely a secondary mineral, and in some cases is formed by alteration of nephelite. But it is also a primary constituent of igneous rocks.

Alteration.—It is decomposed by hydrochloric acid with evolution of CO_2 and yields gelatinous silica. Cancrinite alters to natrolite, but it is seldom found undergoing alteration.

Crystal Form.—Seldom in euhedral crystals, when the forms are the hexagonal prism $m(10\bar{1}0)$ and a flat bipyramid $p(10\bar{1}1)$, Fig. 1. $(10\bar{1}0) \wedge (10\bar{1}1) = 64°$. Usually in subhedral or anhedral crystals, more or less prismatic in shape; frequently quite irregular in form.

FIG. 1.

Cleavage.—Perfect parallel to $m(10\bar{1}0)$, which shows in thin section as distinct straight lines both in cross sections and longitudinal ones. There are also cracks approximately parallel to (0001), and still less distinct ones parallel to $(11\bar{2}0)$. Fracture cracks not particularly noticeable in thin sections.

Optical Properties.—Uniaxial and negative (−). On cancrinite from Miask, $\omega_r = 1.5244$, $\varepsilon_r = 1.4955$, $\omega - \varepsilon = 0.0289$ (Osann). Notable for comparatively strong double refraction, 0.029, equal to that of diopside; also low index of refraction, which is less than that of Canada balsam or of orthoclase feldspar, to which it is very similar. It is recognized in thin sections by its bright interference colors and absence of relief. The uniaxial interference figure is clearly defined, with the first colored ring within the field even in very thin sections, which when 0.02 mm. thick give purple of the first order.

Color.—In thin section, colorless. In crystal masses, various colors in different occurrences; mostly yellow in syenite from Litchfield, Me., from the vicinity of Langesund fjord, Norway, and from the Urals. In Norway also whitish and occasionally blue. At Ditró, Transylvania, flesh-red. The yellow and red colors in some occurrences are derived from inclusions of iron oxide. In cancrinite of Norway the color seems to be of organic origin, disappearing upon heating.

Inclusions.—Cancrinite is usually quite free from inclusions, but in some cases incloses nephelite and in others pyroxene needles, which are frequently arranged with their long axis parallel to the *c* axis of the cancrinite.

Modes of Occurrence.—Cancrinite occurs in alkalic, syenitic, rocks accompanying nephelite or sodalite. In some instances it has developed to the exclusion of nephelite, which it closely resembles in chemical composition. It has not been observed in lava forms of these quartzless alkalic, salic, magmas, in which leucite, nephelite, and sodalite commonly occur. It has not been found in rocks with primary quartz.

Resemblances.—In thin section in ordinary light cancrinite resembles orthoclase feldspar most closely on account of its refraction and cleavage, but is distinguished from it by its strong double refraction. Between crossed nicols its high interference colors cause it to resemble colorless pyroxene or colorless amphibole, but it is readily distinguished from these minerals by its low index of refraction and uniaxial character.

Laboratory Production.—Not yet accomplished.

SCAPOLITE GROUP.

Meionite $=Ca_4Al_6Si_6O_{25}=Me$.
Wernerite $=Me_3Ma_1$ to Me_1Ma_2.
Mizzonite $=Me_1Ma_2$ to Me_1Ma_3.
Marialite $=Na_4Al_3Si_9O_{24}Cl=Ma$.

The scapolite group is an isomorphous series of compounds that may be considered mixtures of $Ca_4Al_6Si_6O_{25}$ and $Na_4Al_3Si_9O_{24}Cl$. The group is somewhat analogous to the lime-soda-feldspar group, having the same elements and varying in composition in a somewhat similar manner. With increase of the sodium molecule (Ma) there is an increase of silica and chlorine and a decrease in alumina, shown by the following table:

	Me Ma	SiO_2	Al_2O_3	CaO	Na_2O	Cl	
Meionite	1:0	40.50	34.40	25.10	—	— =100	
Wernerite	5:1	46.10	30.48	19.10	3.54	1.01=100.23	deduct O for Cl
	2:1	48.03	29.16	17.04	4.76	1.35=100.34	"
	1:1	51.90	26.47	12.90	7.15	2.04=100.45	"
Mizzonite	1:2	55.85	23.73	8.67	9.62	2.75=100.62	"
	1:3	57.85	22.35	6.53	10.87	3.10=100.70	"
Marialite	0:1	63.90	18.10	—	14.70	4.20=100.90	"

Meionite includes compounds ranging from Me_1Ma_0 to Me_3Ma_1; wernerite from Me_3Ma_1 to Me_1Ma_2; mizzonite from Me_1Ma_2 to Me_1Ma_3; and marialite from Me_1Ma_3 to Me_0Ma_1. The transition from one part of the series to another is gradual both chemically and in physical characters.

Alteration.—Meionite is easily decomposed by hydrochloric acid, while at the other end of the series marialite is only slightly attacked. The scapolites alter readily to a variety of minerals, some of which are in the nature of partial replacements by the introduction of other elements than those already present. Among the common alteration products are muscovite, sometimes phlogopite, besides kaolinite, talc, zoisite, epidote, and sometimes chlorite.

Tetragonal; bipyramidal class. $c=0.4393$ (meionite); 0.4384 (wernerite); 0.4424 (mizzonite); 0.4417 (marialite). Euhedral

crystals commonly short thick prisms with $m(110)$ and $a(100)$, terminated by $r(111)$, sometimes $c(001)$, $e(101)$ and the bipyramid of the third kind, $z(311)$, Figs. 1 and 2; also more complex combina-

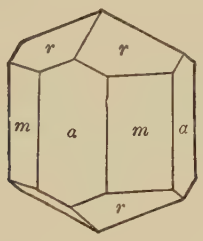

FIG. 1.

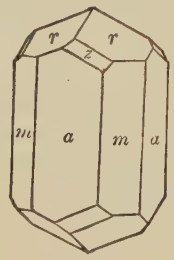

FIG. 2.

tions; anhedral crystals in prismatic aggregates and irregularly shaped grains.

Cleavage parallel to (100) rather perfect; parallel to (110) somewhat less so. Fracture conchoidal. H. = 5–6. Specific gravity = 2.737 in meionite from Mte. Somma to 2.566 in marialite.

Optical Properties.—Optically negative (−). Refraction moderately low, appears to vary with the chemical composition, being higher in the more calcic varieties. But the variableness in the composition of the scapolite at one locality and the absence of sufficient chemical analyses of the material studied optically cause some confusion in the data. The same is true of the double refraction; it varies from being strong in meionite to comparatively weak in mizzonite. The following table has been arranged by Lacroix; in it have been placed in parentheses other data whose position in the series chemically considered is uncertain:

		ω_y	ϵ_y	$\omega - \epsilon$	
$Me—Me_2Ma_1$ (Meionite and wernerite in part)	Hallesta	1.594	1.557	0.037	
	Christiansand	1.592	1.555	0.037	
	Mte. Somma	1.594	1.558	0.036	Des Cloizeaux
	Bolton, Mass.	1.588	1.552	0.036	
	Malsjö	1.588	1.553	0.035	
	(Arendal	1.5894	1.5548	0.0346	Wülfing)
	Bolton, Mass.	1.583	1.552	0.031	
	Lake Baikal	1.581	1.551	0.030	
	Laurinkari	1.583	1.553	0.030	
	Arendal	1.583	1.554	0.029	
$Me_2Ma_1—Me_3Ma_2$ (Wernerite and missonite)	Ersby	1.570	1.547	0.023	
	(Arendal	1.5697	1.5485	0.0212	Zimanyi)
	Arendal	1.566	1.545	0.021	Des Cloizeaux
	(Vesuvius	1.5657	1.5459	0.0189	Kohlrausch)
	(Vesuvius	1.563	1.545	0.018	Franco
	Pargas	1.567	1.550	0.017	
$Me_1Ma_3—Ma$ (Marialite)	Pierrepont	1.562	1.546	0.016	
	Pyrenees	1.558	1.543	0.015	Des Cloizeaux
	(Vesuvius	1.5580	1.5434	0.0146	Wülfing)
	Pouzac	1.5545	1.5417	0.0128	Lattermann

Optical anomalies are rarely observed, but are occasionally shown in the biaxial character of the interference figure with small angle between the optic axes.

Color.—Colorless to white, gray, bluish, greenish, reddish. In thin section colorless, rarely pale colors as given. *Luster*, vitreous to pearly, inclining to resinous.

Inclusions.—Not characteristic; sometimes contains crystals of the minerals associated with it, and fluid inclusions. Dark-colored varieties often contain numerous dark-colored particles of indeterminable character.

Occurrence.—The scapolites occur chiefly in metamorphosed rocks, especially in contact-metamorphosed limestones, and to some extent in the crystalline schists They occur less frequently as secondary minerals in igneous rocks, but do not appear to be of pyrogenetic origin in any case.

Owing to the difficulty in the past of distinguishing the varieties of scapolite from one another optically, those observed in rock sections have generally been described under the group name of scapolite. With the optical variations indicated in Lacroix's table of double refraction it is possible to identify them more closely. Besides the varieties already named there are others based on variations of color or crystal habit. *Dipyre* is a variety of mizzonite in elongated prisms; *couseranite* is identical with dipyre. *Nuttalite, passauite, glaucolite* are varieties of wernerite.

Meionite occurs in cavities in ejected blocks of metamorphosed limestone at Mte. Somma, Vesuvius, as also *mizzonite*. Meionite is found in ejected blocks of similarly altered limestone at Lake Laach.

Wernerite is developed in limestone by contact-metamorphism, when it is often associated with pyroxene, amphibole, garnet, and other minerals, as at numerous localities in New England, New York, and Canada; sometimes with beds of magnetite, as at Arendal, Norway, and at Malsjö, Sweden.

Mizzonite in the form of dipyre or couseranite occurs in metamorphosed limestone at numerous localities in the Pyrenees and elsewhere. It is sometimes filled with minute inclusions of carbonaceous material, or of muscovite, rutile, and quartz. *Marialite* has been found in piperno at Pianura, near Naples.

As already remarked the scapolites found in the crystalline schists and in altered igneous rocks, though varying in chemical composition, have commonly been described simply as scapolite. They are probably

for the most part intermediate in composition between the extreme varieties.

Scapolite is common in pyroxene- and epidote-gneisses, and in amphibolite. It occurs in altered gabbros and in chemically similar rocks, having been formed by the alteration of the lime-soda-feldspar.

Resemblances.—The scapolites are somewhat similar in refraction to the feldspars, quartz, cancrinite, cordierite, wollastonite, prehnite, anhydrite, muscovite, and brucite. They are distinguished from the feldspars by higher double refraction in most cases and by uniaxial character. They differ from quartz in having higher double refraction and in being optically negative; from cancrinite in having higher refraction and tetragonal cleavage. They differ from brucite in cleavage and in being optically negative. From the other minerals, cordierite, wollastonite, prehnite, anhydrite, and muscovite, they differ chiefly in being uniaxial.

Laboratory Production.—Bourgeois has obtained tetragonal crystals that are optically negative, but whose chemical identity has not been determined, by fusing labradorite with white marble. They were accompanied by crystals of anorthite. Other attempts to produce scapolite by processes of fusion have not been successful. Fouqué and Michel-Lévy upon fusing scapolite obtained upon crystallization labradorite and augite.

ZEOLITE GROUP.

Minerals of this group have chemical resemblances in that they are hydrous silicates of aluminium with calcium or sodium, or both, rarely with potassium, barium, strontium. They behave similarly before the blowpipe, fusing with intumescence. They have low refraction, but differ widely in double refraction, and crystallize in different systems. They are almost wholly secondary minerals formed by hydration and alteration of alkalic aluminous silicates, chiefly feldspars, leucite, nephelite, and the sodalites; occurring in cavities, fissures, and as replacements in rocks, mostly igneous, containing the minerals named. They are commonly associated with apophyllite and pectolite, datolite, prehnite, and calcite. Euhedral crystals are in most cases highly characteristic of the different minerals or subgroups within the zeolite group. But anhedral microscopic crystals are in many instances difficult to identify owing to the optical resemblances among certain zeolites. Those that are of more frequent occurrence in rocks are described. They are arranged ac-

cording to their chemical composition and crystallographic resemblances as follows:

Ptilolite	$(Ca,K_2,Na_2)Al_2Si_{10}O_{24}+5H_2O$	
Mordenite	$(Ca,Na_2,K_2)Al_2Si_{10}O_{24}+6\frac{2}{3}H_2O$	Monoclinic
Heulandite	$H_4CaAl_2(SiO_3)_6+3H_2O$	"
Brewsterite	$H_4(Sr,Ba,Ca)Al_2(SiO_3)_6+3H_2O$	"
Epistilbite	$H_4CaAl_2(SiO_3)_6+3H_2O$	"
Phillipsite	$(K_2,Ca)Al_2(SiO_3)_4+4\frac{1}{2}H_2O$	"
Harmotome	$H_2(K_2,Ba)Al_2(SiO_3)_5+5H_2O$	"
Stilbite	$(Na_2,Ca)Al_2Si_6O_{16}+6H_2O$	"
Laumontite	$(H_4CaAl_2Si_4O_{14}+2H_2O$	"
Chabazite	$(Ca,Na_2)Al_2(SiO_3)_4+6H_2O$, pt.	Trigonal
Gmelinite	$(Na_2,Ca)Al_2(SiO_3)_4+6H_2O$	"
Analcite	$NaAl(SiO_3)_2+H_2O$	Isometric
Scolecite	$Ca(AlOH)_2(SiO_3)_3+2H_2O$	Monoclinic
Natrolite	$Na_2Al_2Si_3O_{10}+2H_2O$	Orthorhombic
Thomsonite	$(Na_2,Ca)Al_2(SiO_4)_2+2\frac{1}{2}H_2O$	"
Hydronephelite	$HNa_2Al_3(SiO_4)_3+3H_2O$	Hexagonal
Ranite	$(Na_2,Ca)Al_2(SiO_4)_2+2H_2O$	

PTILOLITE. $(Ca,K_2,Na_2)Al_2Si_{10}O_{24}+5H_2O$.

SiO_2 70.35, Al_2O_3 11.90, CaO 3.87, K_2O 2.83, Na_2O 0.77, H_2O 10.18 = 99.90. The ratio of $Ca:K_2:Na_2 = 6:2:1$ approximately. Hardly acted on by boiling hydrochloric acid.

System of crystallization not known; occurs in short hairlike crystals, aggregated in delicate tufts or forming loose spongy masses.

Cleavage perhaps basal, extinction parallel to the length of the prism. Colorless, white in mass. Luster vitreous. Occurs on bluish chalcedony in cavities in vesicular augite-andesite found in fragments in conglomerate beds of Green Mountain and Table Mountain, Jefferson Co., Colo.

MORDENITE. $(Ca,Na_2,K_2)Al_2Si_{10}O_{24}+6\frac{2}{3}H_2O$.

SiO_2 66.40, Al_2O_3 11.17, CaO 1.94, Na_2O 2.27, K_2O 3.58, H_2O 13.31, (Fe_2O_3 0.57, MgO 0.17) = 99.41. Not perfectly decomposed by acids.

Monoclinic; $a:b:c=0.40099:1:0.42792$, $\beta=88°\ 29\frac{3}{4}'$. Euhedral crystals flattened parallel to $b(010)$ with $c(001)$, $l(450)$, $s(\bar{2}01)$, $t(201)$, Fig. 1, similar to those of heulandite. In groups grown parallel to (010); also radially arranged; hemispherical or cylindrical concretions, with fibrous structure. Cleavage parallel to (010) perfect. Fracture uneven. H.=3–4. Sp. gr.=2.15.

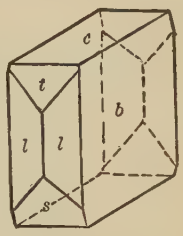

Fig. 1.

Axial plane and the bisectrix X normal to (010); bisectrix Z inclined 73° 30′ to c axis in the acute angle β. Axial angle large; optical character not determined. Double refraction weak.

Color, white, yellowish, or pinkish. In thin section colorless.

Occurrence.—Mordenite occurs in basalt near Morden and at Peter's Point, Nova Scotia; also in vesicular basalt near Hoodoo Mountain, east of the Yellowstone Park, Wyo.

HEULANDITE. $H_4Ca\,Al_2(SiO_3)_6+3H_2O$.

SiO_2 59.2, Al_2O_3 16.8, CaO 9.2, H_2O 14.8=100. Strontium is present in some occurrences. Decomposed by hydrochloric acid without gelatinization.

Monoclinic; $a:b:c=0.40347:1:0.42929$, $\beta=88°\ 34\frac{1}{2}'$. Euhedral crystals sometimes flattened parallel to $b(010)$, with $t(201)$, $s(\bar{2}01)$ prominent, and $c(001)$, $m(110)$, $x(021)$, $a(111)$, Fig. 1. Often in groups of subparallel crystals, producing curved surfaces. Also in globular forms, granular.

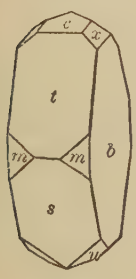

Fig. 1.

Twinning plane (100). *Cleavage* parallel to (010) perfect. Fracture subconchoidal to uneven. H.=3.5–4. Sp. gr.=2.18-2.22.

Optical Properties.—Optically positive (+); axial plane and acute bisectrix Z normal to (010). Axial plane and bisectrix X nearly parallel to (001) in crystals from some localities; in others nearly normal to (001) in white light, Des Cloizeaux. But other crystals show wide variation in the position of the plane of the optic axes with respect to (001), Rinne (see Dana's System of Mineralogy, p. 574). Axial angle, $2V$, varies from 0° to 92°, usually $2E_r=52°$, Des Cloizeaux. Dispersion $\rho<v$ when the axial plane is parallel to (001); $\rho>v$ when nearly normal to (001); crossed dispersion very pronounced, the planes of red and blue axes being inclined from 7° to 12° to one another. Refraction and double refraction low.

$\alpha = 1.498$, $\beta = 1.499$, $\gamma = 1.505$, $\gamma - \alpha = 0.007$, Lévy-Lacroix.

Color, various shades of white passing into red, gray, and brown. In thin section colorless. Luster on (010) pearly, on other faces vitreous.

Occurrence.—Heulandite occurs especially in basaltic rocks with other zeolites in many localities. It is found in gneiss with stilbite and chabazite at Hadlyme, Conn., and Chester, Mass.

BREWSTERITE. $H_4(Sr,Ba,Ca)Al_2(SiO_3)_6 + 3H_2O$.

SiO_2 54.42, Al_2O_3 15.25, SrO 8.99, BaO 6.80, CaO 1.19, H_2O 13.22 = 99.87. This corresponds to the ratio Sr:Ba:Ca = 4:2:1. Decomposed by acids without gelatinization.

Monoclinic; $a:b:c = 0.40486:1:0.42042$, $\beta = 86° 20'$. Crystals prismatic, flattened parallel to $b(010)$ with $a(100)$, $m(110)$, $c(001)$, $e(016)$, Fig. 1.

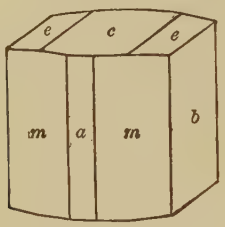

Fig. 1.

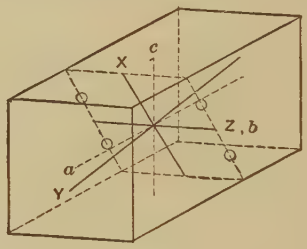

Fig. 2.

Cleavage parallel to (010) perfect; parallel to (100) in traces. Fracture uneven. H. = 5. Sp. gr. = 2.45.

Optical Properties.—Optically positive (+); axial plane and bisectrix Z normal to (010); bisectrix X_r inclined 22° to c axis in the obtuse angle β. Axial angle $2E_r = 94°$, $2E_{bl} = 93°$, in another case $2E_{wh} = 102°$–$103°$, Des Cloizeaux. $2V = 65°$, Lévy-Lacroix. Fig. 2. Dispersion weak, $\rho > v$. Crossed dispersion, planes for red and blue inclined 1° to 2°. Refraction and double refraction low.

$n = 1.45$, $\gamma - \alpha = 0.012$, Lévy-Lacroix.

Color, white, inclining to yellow and gray. In thin section colorless. Luster vitreous; on (010) pearly.

Occurrence.—Brewsterite is found at Strontian in Argyleshire with calcite in gneiss; also at the Giant's Causeway in cavities in basalt; in a calcareous schist near Barèges in the Pyrenees, and elsewhere.

EPISTILBITE.

$H_4CaAl_2(SiO_3)_6 + 3H_2O$.

Composition like that of heulandite, SiO_2 59.2, Al_2O_3 16.8, CaO 9.2, H_2O 14.8 = 100. A little sodium replaces part of the calcium. Soluble with difficulty or imperfectly in concentrated hydrochloric acid without gelatinizing.

Monoclinic; $a:b:c = 0.50430:1:0.58006$, $\beta = 54° 53'$. Euhedral crystals prismatic, uniformly twinned. Forms, $m(110)$, $b(010)$, $c(001)$, $u(011)$, and others, Fig. 1. Anhedral or subhedral crystals in radiated spherical aggregates; also granular.

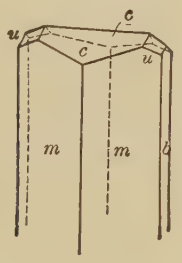

Fig. 1.

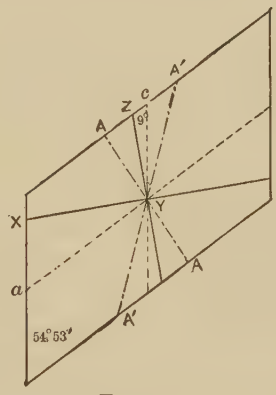

Fig. 2.

Twinning parallel to (100) common; also parallel to (110), sometimes cruciform penetration twins.

Cleavage parallel to (010) perfect. Fracture uneven. H. = 4–4.5; on (010), 3.5. Sp. gr. = 2.25.

Optical Properties.—Optically negative (−); axial plane parallel to (010); obtuse bisectrix Z is inclined $8\frac{1}{2}°$ to $9\frac{1}{2}°$ to the c axis in the obtuse angle β, Fig. 2. Axial angle large, dispersion distinct, $\rho < v$.

$2E_r = 73° 30'$	$2E_y = 75° 35'$	$2E_{gr} = 76° 40'$	Tenne
$= 69° 12'$	$= 70° 45'$	$= 71° 55'$	Klein

Refraction and double refraction low.

Iceland, $\beta = 1.51$, $\gamma - \alpha = 0.010$, Lévy-Lacroix.

Color, colorless to white, flesh-colored, reddish; in thin section colorless.

Occurrence.—Epistilbite is found with scolecite at the Beru fjord, Iceland; on Skye; at Bergen Hill, N. J., and elsewhere.

PHILLIPSITE.

$(K_2,Ca)Al_2(SiO_3)_4+4\frac{1}{2}H_2O$, in part.

SiO_2 48.8, Al_2O_3 20.7, CaO 7.6, K_2O 6.4, H_2O 16.5 = 100. Sodium is sometimes present and a little barium. Gelatinizes with hydrochloric acid.

Monoclinic; $a:b:c = 0.70949:1:1.2563$, $\beta = 55°\ 37'$. Crystals uniformly penetration twins, often resembling orthorhombic forms, Fig. 1, or tetragonal forms. Crystals separate or clustered, in radiating spherulites. Cleavage parallel to (001) and (010) rather distinct. Fracture uneven. H. = 4−4.5. Sp. gr. = 2.2.

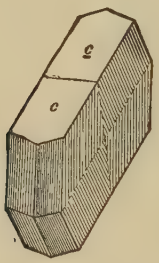

Fig. 1.

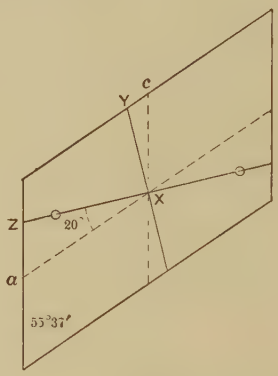

Fig. 2.

Optical Properties.—Optically positive (+); axial plane and obtuse bisectrix X normal to (010); acute bisectrix Z is inclined 15° to 20°, or 30°, to the prismatic crystal axis a in the obtuse angle β, Fig. 2. Axial angle large; dispersion slight, $\rho < v$.

Richmond, $2H_r = 84°\ 8\frac{1}{2}'$, $2H_y = 84°\ 54\frac{1}{2}'$, Des Cloizeaux.

Refraction low, double refraction very low. $\beta = 1.51$-1.57, Des Cloizeaux, $\gamma - \alpha = 0.003$, Lacroix.

Color, white, sometimes reddish. In thin section colorless.

Occurrence.—Phillipsite occurs in basalt at the Giant's Causeway, Ireland; in leucitophyre at Capo di Bove, near Rome; at Aci Castello and elsewhere in Sicily; at various localities in Europe. It has been brought up from the bottom of the Pacific Ocean south of the Hawaiian Islands by the "Challenger," probably connected with the lavas of those islands.

HARMOTOME.

$H_2(K_2,Ba)Al_2(SiO_3)_5+4H_2O$, in part.

SiO_2 47.1, Al_2O_3 16.0, BaO 20.6, K_2O 2.1, H_2O 14.1 = 100. Decomposed by hydrochloric acid without gelatinization.

Monoclinic; in crystals very similar to those of phillipsite in habit and angles; compound twins. It is also similar in optical properties. The axial plane and the acute bisectrix Z are perpendicular to (010), and the plane of the optic axes is inclined somewhat more to the a axis; and the obtuse bisectrix $X \wedge a = 60°$ approximately, in the obtuse angle β, Fig. 1.

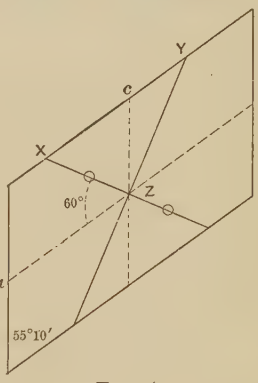

Fig. 1.

$\alpha = 1.503$, $\gamma = 1.508$, $\gamma - \alpha = 0.005$, Lévy-Lacr.

It occurs at Strontian, Scotland; with analcite in Dumbartonshire; in quartz-syenite at Tonsenos near Christiania; in gneiss in New York City, and elsewhere.

STILBITE.

$H_4(Na_2,Ca)Al_2(SiO_3)_6+4H_2O$, in part.

SiO_2 57.4, Al_2O_3 16.3, CaO 7.7, Na_2O 1.4, H_2O 17.2 = 100, in this case Ca : Na = 6 : 1. Decomposed by hydrochloric acid without gelatinization.

Monoclinic; $a : b : c = 0.76227 : 1 : 1.19401$, $\beta = 50° 49\frac{3}{4}'$. Crystals uniformly cruciform penetration twins with twinning plane (001) as in phillipsite, producing pseudo-orthorhombic forms, Fig. 1. Usually in thin crystals tabular parallel to (010). These are often grouped in nearly parallel position, forming sheaf-like aggregates, Fig. 2. Also divergent or radiated, sometimes spherulitic; and in thin lamellar prisms.

Cleavage parallel to (010) perfect. Fracture uneven. H. = 3.5-4. Sp. gr. = 2.094-2.205.

Optical Properties.—Optically negative (−); axial plane parallel to (010); acute bisectrix X inclined about 8° to the a axis in the obtuse angle β, but varies from 0° to 10°; bisectrix Z is inclined 31° 10′ to the c axis in the obtuse angle β; $2E = 52°$ to 53° (blue glass), von Lasaulx; $2V = 33°$, Lévy-Lacroix, Fig. 3. Refraction and double

refraction low. $\alpha=1.494$, $\beta=1.498$, $\gamma=1.500$, $\gamma-\alpha=0.006$, Lévy-Lacroix.

Color, white, occasionally yellow, brown, or red. In thin section colorless. Luster vitreous; on (010) pearly.

Occurrence.—Stilbite is common in cavities in basaltic rocks, as on the Isle of Skye; Arran; in Dumbartonshire, and other localities

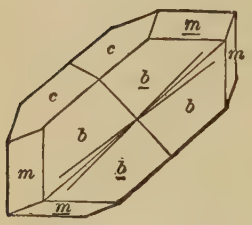

Fig. 1.

Fig. 2.

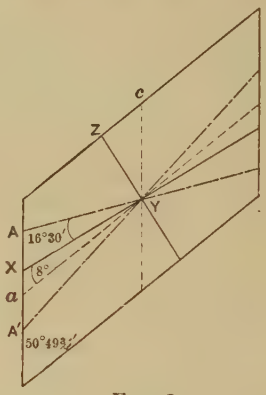

Fig. 3.

in Scotland; at the Giant's Causeway and in the Mourne Mts., Ireland; in the Deccan traps of India; at Bergen Hill, N. J.; in the Lake Superior region; and in many other similar regions of basalt. It also occurs, sometimes in veins, in granite, gabbro, gneiss, and other rocks. It is found in veins in gabbro at Radauthal in the Harz; in granite at Striegau, Silesia; in granite near Falun, Sweden; in gneiss and schist in various localities in the Alps; and in numerous other localities.

LAUMONTITE.

$$H_4CaAl_2Si_4O_{14}+2H_2O.$$

SiO_2 51.1, Al_2O_3 21.7, CaO 11.9, H_2O 15.3 = 100. Gelatinizes with hydrochloric acid.

Monoclinic; $a:b:c=1.1451:1:0.5906$, $\beta=68°\,46\frac{1}{4}'$. Common form of crystal is the prism (110) with an oblique termination by $(\bar{2}01)$; also in anhedral prisms and radiating aggregates. Twinning plane (100).

Cleavage parallel to (010) and (110) very perfect; the prism angle (110) $(1\bar{1}0)$ is 93° 44′; parallel to (100) imperfect. Fracture uneven. H. = 3.5–4. Sp. gr. = 2.25–2.36.

Optical Properties.—Optically negative (−); axial plane parallel to (010); bisectrix Z is inclined 20° to 25° to the c axis in the acute angle β. (45° Lacroix), Fig. 1. Angle between the optic axes medium, dispersion strong, $\rho < v$; $2E = 52°\ 24'$, $2E_{bl} = 56°\ 15'$, Des Cloizeaux. Refraction low, double refraction stronger than in quartz. $\alpha = 1.513$, $\beta = 1.524$, $\gamma = 1.525$, $\gamma - \alpha = 0.012$, Lévy-Lacroix.

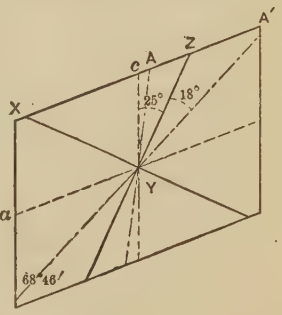

Fig. 1.

Color, white, passing into yellow or gray, sometimes red. In thin section colorless. Luster vitreous, inclining to pearly upon the cleavage faces.

Occurrence. — Laumontite occurs in cavities in basaltic rocks and in other igneous rocks, also in veins in schists and other kinds of rocks.

CHABAZITE.

$(Ca,Na_2)Al_2(SiO_3)_4 + 6H_2O$, in part.

Composition variable, but mostly as given in the formula. If lime is present without soda the proportions are SiO_2 47.4, Al_2O_3 20.2, CaO 11.1, H_2O 21.3 = 100. Soda may be present in amounts up to more than 6 per cent. Decomposed by hydrochloric acid with the separation of slimy silica.

Trigonal; scalenohedral class. $c = 1.0860$, $r \wedge r' = 85°\ 14'$. Euhedral crystals commonly simple rhombohedrons, $r(10\bar{1}1)$ resembling a cube, sometimes with $e(01\bar{1}2)$, $s(02\bar{2}1)$, Figs. 1 and 2, and more

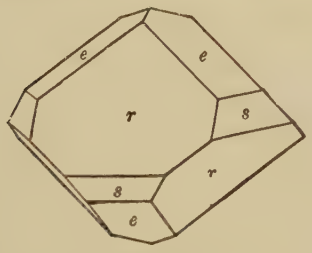

Fig. 1.

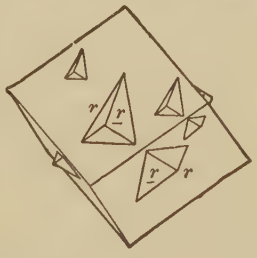

Fig. 2.

complex forms. Also anhedral.

Twinning axis c, penetration twins common (Fig. 2), rarely with $r(10\bar{1}1)$ twinning and composition plane.

Cleavage parallel to $(10\bar{1}1)$ rather distinct. Fracture uneven. H.=4–5. Sp. gr.=2.08–2.16.

Optical Properties.—Optically negative (−); also positive (+) apparently when containing more water. Refraction low and double refraction very low.

$n=1.5$, $\omega-\varepsilon=0.0028$; $n=1.46$, $\omega-\varepsilon=0.002$ herschelite, Lévy-Lacroix. Optically anomalous in places, biaxial with small angle between the optic axes, crystals divided into sectors having different orientations.

Color, white, flesh-red; in thin section colorless. Luster vitreous.

Occurrence.—Chabazite occurs mostly in basaltic rocks, occasionally in other igneous rocks and in gneisses and schists.

GMELINITE.

$(Na_2,Ca)Al_2(SiO_3)_4+6H_2O$, in part.

Composition like that of chabazite with more sodium.

Trigonal; scalenohedral class. $c=0.7345$. Euhedral crystals with hexagonal aspect owing to the combination of the hexagonal prism $m(10\bar{1}0)$ with the plus and minus rhombohedrons $r(10\bar{1}1)$, and $\rho(01\bar{1}1)$ with $c(0001)$, Figs. 1 and 2; also more complex forms and penetration twins.

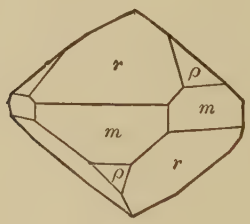

Fig. 1.

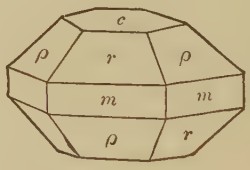

Fig. 2.

Twinning axis c, in penetration twins as in chabazite; also parallel to $(30\bar{3}2)$, which corresponds in position to the unit rhombohedron in chabazite.

Cleavage parallel to $(10\bar{1}0)$ easy; parallel to (0001) sometimes distinct. Fracture uneven. H.=4.5. Sp. gr.=2.04–2.17.

Optical Properties.—Optically positive (+); also negative (−) in some occurrences. Sometimes anomalously biaxial in irregular areas in cross-section. Refraction and double refraction low.

Nova Scotia, $\omega_y = 1.4760$	$\epsilon_y = 1.4674$	$\omega_y - \epsilon_y = 0.0086$	Pirsson
$= 1.4646$	$= 1.4637$	$= 0.0009$	"
$= 1.4770$	$= 1.4765$	$= 0.0015$	"
Montecchio Maggiore $= 1.48031$	$= 1.47852$	$= 0.00179$	Negri

Color, colorless, yellowish, greenish, reddish white, flesh-red. In thin section colorless. Luster vitreous.

Occurrence.—Gmelinite occurs in basaltic and other igneous rocks and in schists, in the same manner as chabazite.

ANALCITE.

$NaAl(SiO_3)_2 + H_2O$.

Hydrous metasilicate of sodium and aluminium, $Na_2O \cdot Al_2O_3 \cdot 4SiO_2 \cdot + 2H_2O = SiO_2$ 54.5, Al_2O_3 23.2, Na_2O 14.1, H_2O 8.2 = 100. Gelatinizes with hydrochloric acid. Alters to hydrous silicate of aluminium, kaolinite, etc.

Crystal Form.—Isometric system. Euhedral crystals commonly icositetrahedrons $n(211)$, Fig. 1, rarely in modified cubes, also in anhedral crystals and aggregates, filling cavities, and as pseudomorphs after leucite, sodalite, and nephelite.

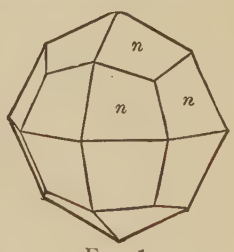

FIG. 1.

Cleavage cubic, in traces. Fracture subconchoidal. H. = 5–5.5. Sp. gr. = 2.22–2.29.

Optical Properties.—Isotropic for the most part in thin section, $n = 1.487$, sometimes exhibiting weak double refraction, which is much more noticeable in freely crystallized analcites. This double refraction is similar to that in some garnets, and appears to be the result of molecular strain due to loss of water.

Color, colorless, white; occasionally with grayish, greenish, yellowish, or reddish tint. In thin section colorless. Luster vitreous.

Modes of Occurrence.—Analcite is commonly a secondary mineral like other zeolites, occurring in igneous rocks in cavities, also replacing other minerals, chiefly nephelite, leucite, and the sodalites, and therefore found frequently in coarsely crystallized rocks and lavas containing these minerals. But it also occurs in ordinary basaltic rocks, as at Bergen Hill, N. J.; in the Lake Superior region; at Table Mt. near Golden, Colo.; on the Cyclopean Islands, near Catania, Sicily, and elsewhere.

Analcite is considered to be a primary pyrogenetic mineral in certain analcite-basalts in the Highwood Mountains and Little Belt Mountains, Mont.;[1] from near Cripple Creek, Colo.,[2] and Sydney, New South Wales;[3] in analcite-tinguaite at Pickard's Point, Manchester, Mass.,[4] and elsewhere. It is also thought to be primary in Mouchiquite from Mount Girnar, Junagarh, India,[5] and of Ampasindava, Madagascar.[6]

Eudnophite from the island of Låven, Langesund fjord, is a cloudy variety of analcite with pronounced double refraction in intersecting laminæ.

Resemblances.—Analcite is most like the colorless sodalites, also leucite, opal, and colorless rock glass. From the glasses of the rock in which it commonly occurs analcite is distinguished by noticeably lower refraction. From sodalite it differs by the character of the cleavage when present, and by chemical tests. From opal and leucite it is distinguished by its cleavage when present, by the more characteristic double refraction frequent in leucite, and by its solubility in acid and by other chemical tests.

Laboratory Production.—Analcite has been obtained by de Schulten in icositetrahedrons, showing double refraction, by heating sodium silicate or caustic soda with an aluminous glass to 180°–190° in a closed tube; also by heating in a similar manner sodium silicate and aluminate in the proper proportions with lime-water.

SCOLECITE.

$$CaAl_2Si_3O_{10}+3H_2O.$$

SiO_2 45.9, Al_2O_3 26.0, CaO 14.3, H_2O 13.8 = 100. Gelatinizes with acids like natrolite.

Monoclinic; $a:b:c = 0.97636:1:0.34338$, $\beta = 89°\ 18'$. In slender prisms parallel to c axis, with $(110) \wedge (1\bar{1}0) = 88°\ 37\frac{1}{2}'$, and (010). Often in divergent groups, also fibrous and radiating.

Twinning plane and composition plane (100).

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[1] Pirsson, L. V. U. S. Geol. Survey, Bull. 237, 1905, pp. 149–158.

[2] Cross, W. Jour. Geol., vol. 5, 1897, p. 684.

[3] Card and Mingaye. Records Geol. Surv., New South Wales, 1902, vol. 7, pt. 2, p. 93.

[4] Washington, H. S. Am. Jour. Sci., 4th Series, vol. 6, 1898, p. 182.

[5] Evans, J. W. Quart. Jour. Geol. Soc., vol. 57, 1901, pp. 38–54.

[6] Lacroix, A. Nouv. Arch. du Muséum, Paris, 4th Series, vol. 1, 1902, p. 197.

Cleavage prismatic parallel to (110) nearly perfect. H.=5-5.5. Sp. gr.=2.16-2.4.

Optical Properties.—Optically negative (−); axial plane and the obtuse bisectrix Z normal to (010); acute bisectrix X inclined about 17° to c axis in the obtuse angle β, Fig. 1. Angle between the optic axes medium. $2E_y = 55°\ 44'$. Iceland $2V_r = 35°\ 22'$, $2V_y = 36°\ 26'$, $2V_{gr} = 37°\ 14'$, Schmidt.

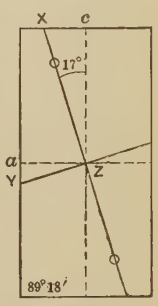

Fig. 1.

Refraction and double refraction low.

$\beta = 1.502$, Des Cloizeaux; also $\beta_y = 1.4952$, Schmidt; $\gamma - \alpha = 0.0083$, Lacroix.

Color, white, in thin section colorless. Luster vitreous, or silky when fibrous.

Occurrence.—Scolecite occurs in basalt in large crystals in the Beru fjord, Iceland; at Staffa; Isle of Mull; Skye; in the Deccan traps of India; in the basalt of Table Mt. near Golden, Colo.; and in similar rocks elsewhere. It occurs in the crystalline schists of the Alps.

NATROLITE.

$Na_2Al_2Si_3O_{10} + 2H_2O$.

Or $Na_2O \cdot Al_2O_3 \cdot 3SiO_2 + H_2O = SiO_2$ 47.4, Al_2O_3 26.8, Na_2O 16.3, H_2O 9.5 = 100. Gelatinizes with acids.

Orthorhombic; $a:b:c = 0.97852:1:0.35362$, $(110) \wedge (1\bar{1}0) = 88°\ 45\frac{1}{2}'$. Also in part monoclinic, $a:b:c = 1.0165:1:0.35991$, $\beta = 89°\ 54\frac{5}{6}'$. Euhedral crystals prismatic with $m(110)$ and $o(111)$, Fig. 1, or with

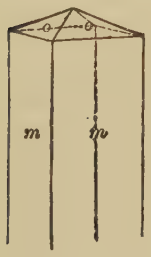

Fig. 1.

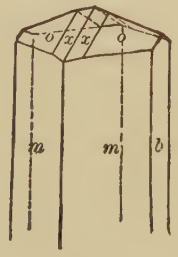

Fig. 2.

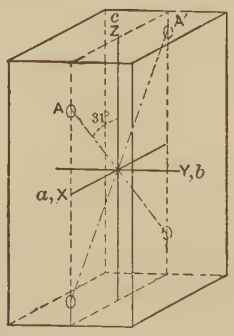

Fig. 3.

$b(010)$ and $X(11\cdot10\cdot11)$, Fig. 2, and other faces. The prismatic angle is nearly 90°, giving the crystals a tetragonal appearance. Crystals commonly very slender acicular prisms with faces striated

parallel to the c axis. Frequently interlacing, divergent, or stellate. Also fibrous, massive, or granular. Commonly the prisms are elongated in the direction of the c axis, but in one instance, from "Brevik," parallel to the b axis.

Twinning plane (301), in cruciform twins crossing at nearly 90° rare.

Cleavage parallel to (110) perfect; parallel to (010) imperfect, perhaps only a plane of parting. Fracture uneven. H.=5-5.5. Sp. gr.=2.20–2.25.

Optical Properties.—Optically positive (+); plane of the optic axes parallel to (010); acute bisectrix Z normal to (001); $X \parallel a$, $Y \parallel b$, $Z \parallel c$. Fig. 3. Angle between the optic axes large; dispersion, $\rho < v$.

Stockö	$2V_r = 61° 56'$,	$2V_y = 62° 15'$,	$2V_{gr} = 62° 34'$ Brögger
Lille Arö	$2V_r = 62° 16\frac{1}{2}'$,	$2V_y = 62° 29\frac{1}{2}'$,	$2V_{gr} = 62° 39\frac{1}{2}'$ Lorenzen

Indices of refraction very low, double refraction low, somewhat higher than that of quartz.

Auvergne	$\alpha_y = 1.4777$	$\beta_y = 1.4808$	$\gamma_y = 1.4901$	$\gamma - \alpha = 0.0124$	Zimanyi
Stockö	$\alpha_r = 1.47287$	$\beta_r = 1.47631$	$\gamma_r = 1.48534$		Brögger
	$\alpha_y = 1.47543$	$\beta_y = 1.47897$	$\gamma_y = 1.48866$	$\gamma - \alpha = 0.01323$	"
	$\alpha_{gr} = 1.47801$	$\beta_{gr} = 1.48172$	$\gamma_{gr} = 1.49181$		"
Lille Arö	$\alpha_r = 1.47577$	—	$\gamma_r = 1.48807$		Lorenzen
	$\alpha_y = 1.47783$	—	$\gamma_r = 1.49047$	$\gamma - \alpha = 0.01264$	"
	$\alpha_{gr} = 1.48030$	—	$\gamma_r = 1.49296$		"

Some natrolite appears to have monoclinic symmetry; that from Aussig and Salesl shows a direction of extinction inclined 5° to 7° to the prismatic edge. That from Lille Arö is apparently monoclinic.

Color, white or colorless, to grayish, yellowish, reddish to red. In thin section colorless. Luster vitreous, inclining to pearly in fibrous varieties.

Occurrence.—Natrolite occurs as a secondary mineral in cavities in basalts in numerous localities and in other vesicular lavas, as in phonolite at Aussig and Teplitz in Bohemia. It occurs in the basalts in Nova Scotia, and at Bergen Hill, N. J. It is also found as an alteration product in nephelite-syenite of the Langesund fjord region, Norway; at Magnet Cove, Ark., and elsewhere as alteration products of nephelite, the sodalite minerals, and of lime-soda-feldspars.

Resemblances.—Natrolite resembles in its low refraction a number of other prismatic zeolites: stilbite, epistilbite, scolecite, harmotome, laumontite; and in double refraction it is like epistilbite and laumontite. It differs from all of those named in being orthorhombic with parallel extinction in most cases. Monoclinic natrolite has lower maximum

extinction angle. Natrolite has higher double refraction than stilbite, scolecite, and harmotome. It is like epistilbite and laumontite in having Z parallel or nearly parallel to the prismatic axis, but differs from both in being optically positive, Z being the acute bisectrix.

Laboratory Production.—Natrolite has been obtained by Doelter by recrystallizing the powdered mineral in water containing carbon dioxide in a closed tube at 160°; also by digesting nephelite in a closed tube at 200° with alkaline carbonates and carbonated water. Analcite was obtained in distinct crystals together with prismatic crystals which were considered natrolite.

THOMSONITE.

$$(Ca,Na_2)_2Al_4(SiO_4)_4+5H_2O.$$

Or $(Ca,Na_2)O\cdot 2Al_2O_3\cdot 4SiO_2+5H_2O$. The ratio of $Ca:Na_2$ varies from 3:1 to 1:1. In some analyses the silica is higher than that required by the formula as given.

	SiO_2	Al_2O_3	CaO	Na_2O	H_2O	
$Ca:Na_2=3:1$	37.0	31.4	12.9	4.8	13.9	= 100
$Ca:Na_2=2:1$	36.9	31.4	11.5	6.4	13.8	= 100
$Ca:Na_2=1:1$	36.8	31.3	8.6	9.5	13.8	= 100

Gelatinizes with hydrochloric acid.

Orthorhombic; $a:b:c=0.99324:1:1.00662$. Euhedral crystals rare; habit prismatic with $a(100)$, $m(110)$, $b(010)$, $c(001)$, $d(401)$, $e(801)$, $y(012)$, Fig. 1. Prismatic faces strongly striated parallel to c axis. Commonly in anhedral prisms, often radiating, in spherical radial concretions, also closely compact.

Cleavage perfect parallel to (010); less so parallel to (100); in traces parallel to (001). Fracture uneven to subconchoidal. H. = 5–5.5. Sp. gr. = 2.3–2.4.

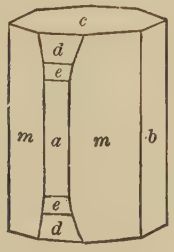

Fig. 1.

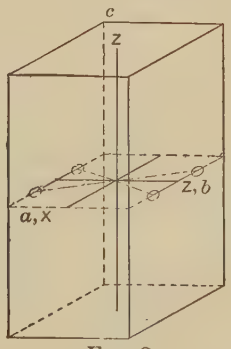

Fig. 2.

Optical Properties.—Optically positive (+); axial plane parallel to (001); acute bisectrix Z normal to (010); $X \parallel a$, $Y \parallel c$, $Z \parallel b$. Angle between the optic axes large; dispersion strong, $\rho > v$, Fig. 2.

Kaaden	$2E_r = 85°\ 45'$	$2E_b = 88°\ 86'$	$2V_r = 53°\ 50'$	Des Cloizeaux
Mte. Somma	$= 86°$	$= 89°\ 53'$		"
Fassathal	$= 93°\ 25'$	$= 96°\ 53'$		"
Dumbarton	$= 82°$–$82°\ 18'$	$= 84°\ 11'$–$84°\ 42'$		"
Bishopton	$2E = 85°$ approx.			Lacroix

Refraction lower than that of orthoclase, double refraction strong. Kaaden $\alpha = 1.497$, $\beta = 1.503$, $\gamma = 1.525$, $\gamma - \alpha = 0.028$, Des Cloizeaux. Thomsonite is the most strongly double-refracting zeolite.

Color, snow-white, reddish, green, impure varieties brown. In thin sections colorless. Luster vitreous, more or less pearly.

Occurrence.—Thomsonite occurs in cavities in lavas and other igneous rocks as a secondary mineral resulting from the alteration of the feldspathic constituents and of nephelite. It also occurs as similar alteration products from lime-soda-feldspars in the crystalline schists. It is found especially near Kilpatrick and at Kilmalcolm and Port Glasgow, Scotland; on Mte. Somma; on Låven, Arö, etc., Langesund fjord; and elsewhere in Europe. It occurs with other zeolites at Peter's Point, Nova Scotia; at Magnet Cove, Ark.; in the Lake Superior Region; and at Table Mountain near Golden, Colo.

Resemblances.—Thomsonite is like cancrinite in refraction and double refraction but differs from it in being biaxial. It differs from all other minerals having equally low refraction by having stronger double refraction.

HYDRONEPHELITE.

$$HNa_2Al_3Si_3O_{12} + 3H_2O.$$

Or $2Na_2O \cdot 3Al_2O_3 \cdot 6SiO_2 \cdot 7H_2O = SiO_2$ 39.3, Al_2O_3 33.4, Na_2O 13.5, H_2O 13.8 = 100. When Ca replaces part of the sodium the mineral has been called *ranite* (with about 5 per cent. CaO). Soluble in hydrochloric acid with gelatinization.

Hexagonal (?); massive with radiated fibrous or scaly structure. Prismatic cleavage indistinct in three directions in basal plates. H. = 4.5–6. Sp. gr. = 2.263.

Optical Properties.—Optically uniaxial and positive (+). Refraction and double refraction about the same as in natrolite, that is, $\frac{2\omega + \varepsilon}{3} = 1.49$. $\varepsilon - \omega = 0.012$, approx. Rosenbusch.

Color, white, also dark gray to grayish black. In thin section colorless, sometimes clouded by dark-colored dust-like particles. Luster vitreous.

Occurrence.—*Hydronephelite* was first described as an alteration product from nephelite, associated with sodalite, in the nephelite-syenite at Litchfield, Me. Longitudinal sections show a prismatic cleavage which in cross sections appear to lie in three directions, indicating that the crystals are trigonal or hexagonal. (Diller.) It is common as an alteration product of nephelite in other nephelite-syenites, and is often accompanied by thomsonite, ægirite, and diaspore.

Ranite occurs as an alteration product of nephelite in nephelite-syenite on Låven, Langesund fjord.

Summary of Optical Characteristics.

The zeolites are all characterized by low refraction, the maximum being lower than that of Canada balsam, except for one determination on phillipsite (1.57). Most of them are lower than orthoclase. With one exception, thomsonite, all exhibit low double refraction, ranging from 0.002-0.012.

Owing to the wide range of crystal symmetry assumed by these minerals no further general statements as to optical characters can be made.

Analcite, which crystallizes in the isometric system, is distinguished from other zeolites by its isotropic character.

Chabazite and *gmelinite* are alike in being optically uniaxial with variable optical character (±) and very low double refraction. But they differ from one another in cleavage and in chemical composition.

Hydronephelite, also uniaxial and optically positive, has stronger double refraction; $\epsilon - \omega = 0.012$.

Natrolite and *thomsonite* occur in prisms or fibers with parallel extinction, but in natrolite the prism axis is parallel to Z and the double refraction is very low, 0.002, while in *thomsonite* the prism axis is Y and the double refraction is strong, 0.028.

Of the monoclinic zeolites those that are prismatic in habit exhibit inclined extinction to various extents. In *stilbite* and *scolecite* the prism axis is the direction of vibration of the fastest ray, X; in *phillipsite* and *laumontite* it is the direction of vibration of the slowest ray, Z. In *harmotome* and *mordenite* it corresponds to Y and is therefore faster or slower than the ray vibrating at right angles to it according to the position of the prism with respect to the direction of the transmitted light. Of these minerals, *stilbite* has the lowest

extinction angle, 8° approximately; the others are nearly alike, from 15° to 20°.

Stilbite and *scolecite* agree in having the prism axis the direction of vibration of the fastest ray. They also agree in refraction and double refraction, but differ in the maximum extinction, 8° in stilbite, 17°–22° in scolecite. Stilbite is sometimes lamellar.

Phillipsite and *laumontite* are alike in having the prism axis nearest Z, the direction of vibration of the slowest ray, with nearly the same maximum angle of extinction, and similar refraction, but phillipsite has very low double refraction, 0.003, and laumontite considerably higher, 0.012.

Epistilbite, when prismatic, resembles phillipsite and laumontite in having Z near the prism axis, but the extinction angle is 9°. The double refraction is near that of laumontite.

Heulandite and *brewsterite* are commonly lamellar with distinct cleavage parallel to the plane of lamination. In heulandite and brewsterite the acute bisectrix Z is normal to the cleavage plane, but the optic angle is generally small in heulandite, and larger in brewsterite. They are easily distinguished chemically

APOPHYLLITE.

$$H_7KCa_4(SiO_3)_8 + 4\tfrac{1}{2}H_2O.$$

SiO_2 53.7, CaO 25.0, K_2O 5.2, H_2O 16.1 = 100. A small amount of fluorine replaces part of the oxygen. Decomposed by hydrochloric acid, with separation of slimy silica.

Tetragonal; $c = 1.2515$. Euhedral crystals varied in habit, usually in short prisms with $a(100)$ and $c(001)$ dominant, and $p(111)$, sometimes $y(310)$, subordinate, Fig. 1; or prismatic with $p(111)$, Fig. 2,

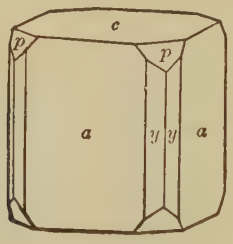

Fig. 1.

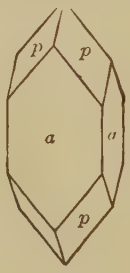

Fig. 2.

also pyramidal, with (111) dominant; less often thin tabular parallel to (001). Faces (001) often rough; (100) bright but striated ver-

tically. Anhedral crystals, granular, lamellar, rarely in radiating prisms or concentric lamellæ.

Twinning parallel to (111) rare.

Cleavage parallel to (001) highly perfect; parallel to (110) less so. Fracture uneven. H.=4.5–5. Sp. gr.=2.3–2.4.

Optical Properties.—Optically positive (+); sometimes negative (−). In some varieties optically anomalous. Refraction low, double refraction very low.

Andreasberg	$\omega_r = 1.5309$	$\varepsilon_r = 1.5332$	$\varepsilon_r - \omega_r = 0.0023$	Luedecke
"	$\omega_y = 1.5337$	$\varepsilon_y = 1.5356$	$\varepsilon_y - \omega_y = 0.0019$	"
"	$\omega_y = 1.5346$	$\varepsilon_y = 1.5365$	$= 0.0019$	Zimanyi
Collo, Algiers	$\omega_r = 1.5328$	$\varepsilon_r = 1.5343$	$\varepsilon_r - \omega_r = 0.0015$	Gentil
" "	$\omega_y = 1.5347$	$\varepsilon_y = 1.5368$	$\varepsilon_y - \omega_y = 0.0021$	"
Faroe	$\omega_r = 1.5311$	$\varepsilon_r = 1.5335$	$= 0.0024$	Luedecke
	$\omega_y = 1.5356$	$\varepsilon_y = 1.5368$	$= 0.0012$	"
Seisseralp	$= 1.5340$	$= 1.5368$	$= 0.0028$	Zimanyi
Poonah	$= 1.5343$	$= 1.5369$	$= 0.0026$	"

The optical anomalies of apophyllite appear in the interference figures in sections normal to the optic axis. In some cases the rings accompanying the interference cross are black and white instead of colored. In other cases the red rings are wanting. These irregularities in the disposition of the interference rings for different kinds of light are assumed by Klein to be due to an irregular superposition of positive and negative crystals, in layers and thin wedges.

In many cases basal sections of apophyllite in parallel polarized light between crossed nicols are divided into areas with different optical properties. There is a central square which is uniaxial, remaining dark during a rotation of the plate, and surrounding it four sectors that are biaxial with optical angle from 0° to 50° for red and 60° for blue, the plane of the axes for blue being at right angles to that for red. These anomalies may be produced by lateral pressure or by changes of temperature. They are probably the result of molecular strain induced by change of physical conditions subsequent to the crystallization of the mineral.

Color, colorless to white, grayish; occasionally with a greenish, yellowish, or rose-red tint, also flesh-red. In thin section colorless. Luster vitreous; on (001) pearly.

Occurrence.—Apophyllite occurs in cavities and cracks in basaltic and similar rocks as a secondary mineral with the zeolites. It is sometimes found in granite and gneiss.

Resemblances.—Apophyllite resembles some of the zeolites in its low double refraction, but it has a higher refraction than most

of them, and is most like chabazite and gmelinite in being uniaxial, with variable optical character (±), but differs from them in having basal cleavage.

Laboratory Production.—Apophyllite has been obtained from a solution of its constituents in water containing carbon dioxide, heated in a closed tube at 150°–160° (Doelter). It has been dissolved in water heated to 180° under a pressure of 10 to 12 atmospheres and recrystallized upon cooling (Wöhler). It has been formed by the action of a solution of potassium silicate on plates of gypsum (Becquerel). It has formed in the ruins of Roman works at the hot springs at Plombières.

ANDALUSITE.

Al_2SiO_5.

$Al_2SiO_5 = Al_2O_3 \cdot SiO_2$, from which Al_2O_3 63.2, SiO_2 36.8 = 100.

A little iron is usually present. Andalusite from Vestanå, Sweden, contains 6.91 per cent Mn_2O_3. Not decomposed by acids. Alters to muscovite and kaolin.

Orthorhombic; $a:b:c = 0.98613:1:0.70245$. Seldom in euhedral crystals, commonly in rough prisms $m(110)$ in combination with $c(001)$ and $s(011)$, Fig. 1. The prismatic angle is near 90° (89° 12′). The length of the prisms is 3 or 4 times the width. In prismatic

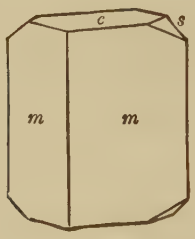

Fig. 1.

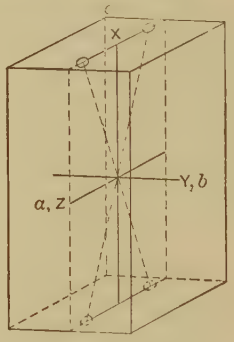

Fig. 2.

aggregates, sometimes divergent; also in anhedral grains and lenticular forms.

Cleavage parallel to (110) distinct; parallel to (100) less perfect, a gliding plane; parallel to (010) in traces. Fracture uneven, subconchoidal. H. = 7.5. Sp. gr. = 3.16-3.20.

Optical Properties.—Acute bisectrix X, optically negative (−). Axial plane parallel to (010), $X \parallel c$, $Y \parallel b$, $Z \parallel a$. $2V_r = 83° 37'$, Fig. 2.

$\alpha_r = 1.632$, $\beta_r = 1.638$, $\gamma_r = 1.643$, $\gamma_r - \alpha_r = 0.011$. Brazil, Des Cloizeaux.

Color, whitish, rose-red, flesh-red, violet, pearl-gray, reddish brown, olive-green, grass-green. In thin section transparent to pale reddish. Pleochroism in thick plates: X dark blood-red, Y oil-green, Z olive-green. In thin section X rose-red, Y, Z colorless to greenish. $X > Y > Z$, Haidinger. X intense pure yellow, Y, Z blue-green with tinge of grass-green, manganese-andalusite, Bäckström. Color sometimes distributed in irregular spots, especially about inclusions constituting "pleochroic halos." A zonal structure has been observed in andalusite of Graubunden in which the center is red, the margin colorless.

Inclusions.—Andalusite frequently contains abundant inclusions of graphite and carbonaceous matter, less often crystals of the minerals associated with it. The carbonaceous matter is sometimes so distributed as to leave long tapering prismatic portions of the andalusite crystals comparatively free from inclusions. These are so arranged in the crystal that cross sections of the andalusite exhibit a tesselated appearance, sometimes resembling a light-colored cross. Fig. 3.

Fig. 3.

Such andalusites are called *chiastolite*. A variety found in Finland in which the inclusions are minute crystals of biotite and magnetite, has been called *maltesite* by Sederholm.

Occurrence.—Andalusite is frequently developed in argillaceous schists and clay slates by contact metamorphism from igneous bodies, as in the andalusite-hornfels of the metamorphic zone about granite of Barr and Andlau in the Vosges described by Rosenbusch; in Brittany; in the Lake District of England, and elsewhere. According to Rosenbusch andalusite develops especially in sedimentary rocks rich in aluminium and low in calcium, which may or may not contain considerable magnesium. In such rocks it is often accompanied by biotite and cordierite, but rarely by sillimanite.

Andalusite also occurs in some gneisses, mica-schists, and phillites, where it is associated with sillimanite and cyanite, also with cordierite, garnet, corundum, and tourmaline. It is sometimes regularly intergrown with sillimanite in crystallographically parallel orientation. Less often the two minerals have (100) in common, but the c axes

apparently perpendicular or inclined 45° to one another. When andalusite has been found in granite it appears to be intimately associated with inclusions of sedimentary rocks.

Resemblances.—Andalusite resembles more or less closely sillimanite, diaspore, topaz, zoisite, thulite, and kornerupine. From sillimanite it is distinguished by the optical orientation, the prismatic axis being X in andalusite, and by weaker double refraction. It is distinguished from diaspore by much lower double refraction; from topaz by cleavage and the character of the acute bisectrix; from zoisite by the orientation of the acute bisectrix and by the cleavage; from thulite by the position of the plane of the optic axes and the size of the angle between the optic axes; and from kornerupine also by the greater size of the angle between the optic axes.

SILLIMANITE.

Al_2SiO_5.

Or $Al_2O_3 \cdot SiO_2$; from which Al_2O_3 63.2, SiO_2 36.8 = 100, like andalusite. Unattacked by acids.

Orthorhombic; $a:b = 0.970:1$. Prismatic crystals without distinct terminal faces. In the prismatic zone, $a(100)$, $b(010)$, $m(110)$, $h(230)$. Angles $mm''' = 88°\ 15'$, $hh' = 69°$. Prism faces striated and rounded, often long and slender, sometimes fibrous; prisms in parallel or divergent groups; sometimes curved or bent; pointed, or abruptly terminated as though broken.

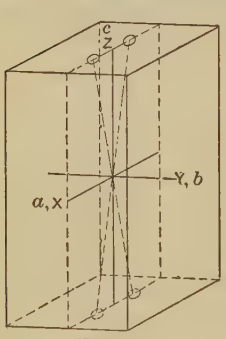

FIG. 1.

Cleavage parallel to (010) perfect. Fracture uneven. H. = 6–7. Sp. gr. = 3.23–3.24.

Optical Properties.—Optically positive (+). Acute bisectrix Z parallel to c axis. Plane of the optic axes parallel to (010). $X \parallel a$, $Y \parallel b$, $Z \parallel c$, Fig. 1. Axial angle small, dispersion strong, $\rho > v$.

Saybrook	$2E_r = 43°\ 9'$	$2E_y = 42°\ 30'$	$2E_{bl} = 38°\ 41'$	Des Cloizeaux
Bamle	$2E_r = 37°\ 55'$	$2E_{gr} = 33°\ 50'$	$2E_v = 28°\ 20'$	"
Ceylon	$2V_r = 31°\ 19'$	$2V_y = 30°\ 57'$	$2E_{gr} = 30°\ 35'$	Melczer
Mont Pelat	$2V = 20°$ approx.			Lévy and Termier

Indices of refraction and double refraction moderately high, varying slightly with the color, the darker-colored sillimanite having the lower indices of refraction as determined by Hlawatsch.

Saybrook	$\alpha_y = 1.6603$	$\beta_y = 1.6612$	$\gamma_y = 1.6818$	$\gamma - \alpha = 0.0215$	Wülfing
"	$= 1.6570$	$= 1.6583$	$= 1.6770$	$= 0.0200$	Zimanyi
Morlaix	$= 1.659$	$= 1.661$	$= 1.680$	$= 0.021$	Lacroix
Ceylon	$= 1.658$	$= 1.659$	$= 1.678$	$= 0.020$	"
"	$= 1.6562$	$= 1.6577$	$= 1.6766$	$= 0.0204$	Melczer

Color, hair-brown, grayish brown, grayish white, grayish green, pale olive-green. In thin section colorless. In thicker crystals pleochroic.

Saybrook, *X* light brownish, *Z* dark clove-brown, Rosenbusch. Ceylon, *X* pale yellow to brownish yellow *Y*, pale green to gray-green, *Z* deep blue with pale violet tint, Melczer.

Occurrence.—Sillimanite occurs chiefly in gneiss and crystalline schists, less often in zones of contact metamorphism; rarely in granite and other igneous rocks. It occurs as separate crystals or in aggregates of fibers, in diverse or radiating arrangement. It is frequently developed along gliding planes in sheared schist. It is found in many localities, often accompanied by garnet, cordierite, corundum, andalusite, and cyanite.

Fibrolite, bucholzite, monrolite, bamlite, xenolite, wörthite are varieties of sillimanite, mostly fibrous with impurities of quartz.

Resemblances.—Sillimanite resembles andalusite, diaspore, zoisite, kornerupine, and scapolite. It differs from all of these minerals by having the prismatic axis, *Z*, the direction of vibration of the slowest ray. It differs from andalusite, zoisite, and kornerupine by having stronger double refraction; from diaspore by having weaker double refraction; and from scapolite by cleavage and biaxial characters.

Laboratory Production.—Sillimanite has been produced in the open crucible from silicate solutions rich in aluminium; also in the manufacture of porcelain. Sillimanite results from the heating to 1320°–1350° of andalusite, cyanite, topaz, and kaolin.

CYANITE (Disthene).

Al_2SiO_5.

$Al_2O_3 \cdot SiO_2$, like andalusite and sillimanite, sometimes with a little Fe_2O_3. Not attacked by acids. Rarely altered to muscovite.

Triclinic; $a:b:c = 0.89938:1:0.70896$. $\alpha = 90°\ 5\frac{1}{2}'$, $\beta = 101°\ 2\frac{1}{4}'$, $\gamma = 105°\ 44\frac{1}{2}'$. Commonly in long bladed crystals, flattened parallel to (100), with (010) and (110) prominent. Rarely terminated by

crystal planes, (001) and others; often irregularly terminated or fibrous.

Twinning.—(1) (100) twinning and composition plane, often polysynthetic; (2) twinning axis the normal to the edge (100) (010) lying in the plane (100); (3) twinning axis the edge (100) (010), the composition plane (100); (4) twinning and composition plane (001), often polysynthetic as a result of pressure; (5) twinning plane $(\bar{2}\bar{1}2)$, penetration twins cruciform like staurolite with the c axes intersecting at about 60°.

Cleavage.—(100) very perfect; (010) less perfect; also parting parallel to (001), the gliding plane in which lamellar twinning is produced by pressure; another gliding plane is $(\bar{3}08)$. H. from 4–7, variable with position on crystal; 4–5 on (100) parallel to axis c; 6–7 on (100) parallel to the edge (100) (001); 7 on (010). Sp. gr. = 3.559 white, 3.675 blue.

Optical Properties.—Optically negative (−). The acute bisectrix X is almost normal to (100), the plane of the optic axes inclined about 30° to the edge (100) (010). The angle between the optic axes is large, $2V_y = 82°\ 10'$, Wülfing; $2V_r = 82°\ 16'$ and $82°\ 44'$, Des Cloizeaux. Dispersion $\rho > v$, slightly inclined and distinctly crossed. Index of refraction high, double refraction low.

$\alpha_y = 1.7171$, $\beta_y = 1.7222$, $\gamma_y = 1.7290$, $\gamma_y - \alpha_y = 0.0119$ Wülfing
$\alpha = 1.712$, $\beta = 1.720$, $\gamma = 1.728$, $\gamma - \alpha = 0.016$ Lévy-Lacroix

Color, blue, white; often middle of blade blue, margin white; also gray, green, and black from inclusions. In thin section colorless, light blue to greenish blue. Pleochroism weak, only noticeable in strongly colored crystals, between colorless and blue.

Occurrence.—Cyanite is developed especially in the crystalline schists, being sometimes found in zones of contact metamorphism. It does not occur as a pyrogenetic mineral in igneous rocks. It occurs in gneiss and mica-schist, associated with garnet and staurolite. It is found in numerous European and American localities. It frequently accompanies corundum as an alteration product.

Resemblances.—Cyanite is like a number of prismatic minerals in some of its optical properties, but differs from them in general by its inclined extinction in the prism zone; thus from andalusite, sillimanite, and similar orthorhombic minerals; also from prismatic zoisite. From the blue minerals, dumortierite and serendibite, it is distinguished by the weakness of its color in thin section.

TOPAZ.

$(Al(O,F_2))AlSiO_4$.

Or $Al_2SiO_4(O,F_2)$. Composition nearly the same as that of andalusite with the addition of fluorine and a variable amount of hydroxyl. When the ratio of $O:F_2 = 5:1$, then SiO_2 33.3, Al_2O_3 56.5, F 17.6 = 107.4, deduct (O = 2F) 7.4 = 100. This accords closely with analyses of topaz from various localities. Only partially attacked by sulphuric acid. Alters to muscovite and kaolin.

Orthorhombic; $a:b:c = 0.528542:1:0.476976$. Euhedral crystals commonly short prisms, $m(110)$ predominating, or $l(120)$, prisms then nearly square. Faces in prism zone often striated parallel to the c axis. Terminal planes $c(001)$, $f(021)$, $y(041)$, $u(111)$, $o(221)$, and others, Figs. 1 and 2. Anhedral crystals in rocks, prisms in parallel or divergent groups; also in grains.

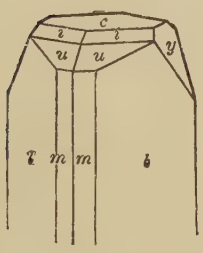

Fig. 1.

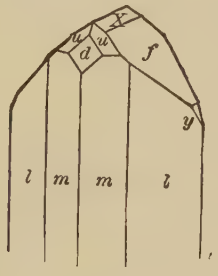

Fig. 2.

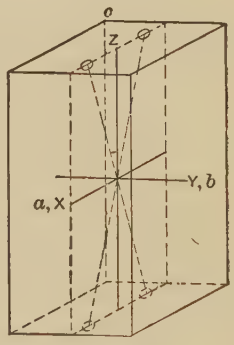

Fig. 3.

Cleavage.—(001) highly perfect; but very imperfect parallel to (201) and (021) as shown by the percussion figure. Fracture subconchoidal to uneven. H. = 8. Sp. gr. = 3.532 Minas Geraes, Brazil; 3.574, Zacatecas. See also the specific gravity data in table of optical properties.

Optical Properties.—Optically positive (+). Axial plane parallel to (010); acute bisectrix Z normal to (001). $X \parallel a$, $Y \parallel b$, $Z \parallel c$, Fig. 3. Axial angle variable, even in one crystal; according to Penfield and Minor it varies with the amount of F replaced by OH, as do also the indices of refraction and the specific gravity.

	$2E_y$	Sp. gr.	α_y	β_y	γ_y	F	H_2O
Durango	129° 3′	—	—	—	—	—	—
						Des Cloizeaux	
Zacatecas	126° 28′	3.574	—	—	—	—	0.18
Thomas Range, Utah	125° 53′	3.565	1.6072	1.6104	1.6176	20.37	0.19
						Alling (126° 24′)	
Nathrop, Colo.	125° 51′	3.567	—	—	—	20.42	0.29
Pikes Peak, Colo.	122° 42′	3.567	—	—	—	—	0.48
Tenagari, Japan	120° 59′	3.565	—	—	—	19.50	0.57
Adun Tschalon	118° 46′	3.562	1.6133	1.6160	1.6225	19.28	0.58
						Mulheims (121° 55′)	
San Luis Potosi	118° 17′	3.575	—	—	—	19.53	0.80
Schneckenstein	114° 28′	3.555	1.6155	1.6181	1.6250	18.50	0.93
						Mulheims (114° 17′)	
Stoneham, Me.	113° 50′	3.560	—	—	—	18.56	0.98
Minas Geraes, Brazil	84° 28′	3.532	1.6294	1.6308	1.6375	15.48	2.45
						Mulheims (86° 21′)	
Mugla, Asia Minor	71° 13′	—	—	—	—	—	—

$2V_y = 65°\ 30\frac{1}{2}'$ Adun Tschalon; $2V_y = 62°\ 33'$ Schneckenstein; $2V_y = 49°\ 37'$ Minas Geraes (Mulheims). Dispersion, $\rho > v$. Double refraction low, decreasing with increasing hydroxyl. $\gamma - \alpha = 0.0104$, 0.0092, 0.0095, 0.0081 in the cases given in the table. Optical anomalies occur in some crystals of topaz, especially those from Brazil. It is probably due to a variation in chemical composition in different parts of the crystal and a consequent variation in the density from which may result molecular strain.

Color, colorless, straw-yellow, wine-yellow, white, grayish, greenish, bluish, reddish. In thin section colorless. Luster vitreous.

Inclusions.—Topaz sometimes contains numerous fluid inclusions, consisting, in the crystals from Brazil, of water, liquid carbon dioxide, and possibly another liquid (Brewster). There are besides crystals of several kinds of soluble salts within the fluid, whose characters have not been determined. The same topaz often carries microscopic crystals of hematite and ilmenite.

Occurrence.—Topaz occurs in some granites and pegmatites, especially those containing cassiterite, fluorite, tourmaline, and beryl, in many localities. It occurs in cavities with spessartite in rhyolite at Nathrop, and Chalk Mountain, Colo.; and similarly in rhyolite of the Thomas Range, Utah. It is also common in certain zones of contact metamorphism about granite in which the rocks are impregnated with abundant topaz, producing topaz-fels, as at Schneckenstein, or the topazised quartz-porphyries of the Erzgebirge.

Resemblances.—Topaz is optically most like andalusite, from which it is distinguished by the cleavage. From sillimanite it is

distinguished by lower double refraction and by the difference in the rays vibrating parallel to the prism axis in each mineral. Topaz somewhat resembles quartz and orthoclase with which it is associated, but is characterized by higher refraction, and in contradistinction to quartz by its cleavage; the sections parallel to the cleavage exhibiting a biaxial interference figure. It is distinguished from orthoclase by cleavage and optical orientation.

Laboratory Production.—Topaz has been obtained by Friedel and Sarasin by the action of hydrofluosilicic acid on silica and alumina in the presence of water at 500°.

DUMORTIERITE.

$Al_{20}Si_7O_{44}$.

A basic aluminium silicate, $(AlO)_{16}Al_4(SiO_4)_7$ or $10Al_2O_3 \cdot 7SiO_2 = SiO_2$ 29.2, Al_2O_3 70.8 = 100. Part of the aluminium may be replaced by boron. B_2O_3 reaches 6.14 per cent. in dumortierite from Harlem, N. Y. Not attacked by acids, not even hydrofluoric acid.

Orthorhombic; $a:b:=0.5317:1$. Prismatic angle 56° approx. Rarely in distinct crystals with (100) and (110), not terminated by crystal faces. Usually in prismatic to fibrous aggregates.

Twinning on (110) sometimes repeated, forming trillings.

Cleavage (100) distinct; also prismatic, imperfect. Fracture nearly perpendicular to axis of prism. H. = 7. Sp. gr. = 3.22, Link; 3.265, Diller; 3.36, Damour.

Optical Properties.—Optically negative (−). Axial plane parallel to (010). Acute bisectrix X normal to (001). $X \parallel c$, $Y \parallel b$, $Z \parallel a$. $2V = 30°$. Fig. 1. Dispersion $\rho > v$, Tvedestrand, Lévy-Lacroix; $\rho < v$, Beaunan, Bertrand. Index of refraction moderately high.

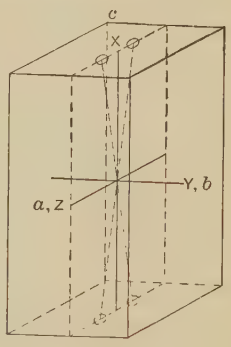

FIG. 1.

Val Donbastone $\alpha_y = 1.678$, $\beta_y = 1.686$, $\gamma_y = 1.689$, $\gamma - \alpha = 0.011$, Linck.
Tvedestrand — $\beta = 1.65$, — $\gamma - \alpha = 0.010$, Lévy-Lacroix.

Color, bright smalt-blue to greenish blue, rarely white to colorless or bluish green to pistachio-green. In thin section strongly pleochroic from colorless to intense blue; X deep blue, Y yellowish to reddish violet, Z colorless. In the variety from Val Donbastone $X = Y$ nearly colorless, Z pistachio-green with a tinge of yellow or blue. Luster vitreous.

Occurrence.—Dumortierite occurs sparingly in granitic pegmatite and in gneiss. It is found in pegmatite at Beaunan and Brignais near Lyons, France; near the latter locality it is accompanied by tourmaline, cordierite, and apatite. It occurs with cordierite at Tvedestrand, Norway; with corundum in pegmatite at Wolfshau, Silesia. It has been found in pegmatite near Harlem, N. Y.; and in a quartzose rock at Clip, Ariz.; also in spherulitic aggregates in a fine-grained quartz dike in Skamania Co., Washington.

Resemblances.—Dumortierite resembles the blue minerals serendibite, sapphirine, and grandidierite in color and somewhat in refraction. It is distinguished from serendibite and sapphirine by its system of crystallization, and from grandidierite by its prismatic habit.

PYROXENE GROUP.

COMPOSITION: $RSiO_3$ with R = Ca, Mg, Fe, also Mn, Zn.

$RSiO_3$.

$R(Fe,Al)_2SiO_6$ with R = Mg, Fe.

Less often with

$RAl(SiO_3)_2$ with R = Na.

$\overset{I}{R}\overset{III}{R}(SiO_3)_2$ with $\overset{I}{R}$ = Na, Li, $\overset{III}{R}$ = Al, Fe.

Orthorhombic, Monoclinic, and **Triclinic Systems.**—While belonging to three systems of crystallization, pyroxenes agree in general crystal habit. They have a prism with an angle of about 93° and 87°, parallel to which there is a more or less well-defined cleavage. Other crystal forms agree closely in angles. There are isomorphous series in the orthorhombic and in the monoclinic systems, and close relationship between the two series shown by frequent parallel intergrowths of orthorhombic and monoclinic forms. They have close similarity in optical properties. The triclinic pyroxenes are less closely related to the other forms, and are less frequently met with as rock-making minerals.

Owing to the wide range of physical characters and the diversity of composition among the members of this large group no attempt will be made to summarize them as a whole, but they will be treated in groups according to their system of crystallization and to other relationships. A list of the chief rock-making pyroxenes and their simplified formulas follows:

ORTHORHOMBIC PYROXENES.

Enstatite, $MgSiO_3$.

Bronzite.

Hypersthene, $(Mg,Fe)SiO_3$.

MONOCLINIC PYROXENES.

Diopside, $\begin{cases} CaMg(SiO_3)_2. \\ Ca(Mg,Fe)(SiO_3)_2. \end{cases}$

Malacolite, Salite, Diallage, etc.

Hedenbergite, $CaFe(SiO_3)_2$.

Manganhedenbergite, containing Mn.

Schefferite, $(Ca,Mg)(Fe,Mn)(SiO_3)_2$.

Jeffersonite, containing Zn.

Augite, $\begin{cases} m[Ca(Mg,Fe)(SiO_3)_2]. \\ n[(Mg,Fe)(Al,Fe)_2SiO_6]. \\ \quad \text{Sometimes } Na(Al,Fe)(SiO_3)_2. \end{cases}$

Diallage in part, ægirite-augite.

Acmite, $Na^{III}Fe(SiO_3)_2$.

Ægirite.

Jadeite, $NaAl(SiO_3)_2$.

Spodumene, $LiAl(SiO_3)_2$.

Låvenite, $Na_2(Mn,Ca,Fe)(ZrO\cdot F)(SiO_3)_2$.

Wöhlerite, $12(Na_2,Ca)(Si,Zr)O_3\cdot RNb_2O_6$ with F.

Rosenbuschite, $Na_2Ca_3((Si,Zr,Ti)O_3)_4$.

Pectolite, $HNaCa_2(SiO_3)_3$.

Wollastonite, $CaSiO_3$.

TRICLINIC PYROXENE.

Hiortdahlite, $4Ca(Si,Zr)O_3\cdot Na_2ZrO_2F_2$.

From the above list it will be observed that the simple magnesium metasilicate is orthorhombic, the calcium metasilicate is monoclinic. The iron metasilicate does not occur alone in the pyroxene group, but is found as a monoclinic amphibole.

The orthorhombic pyroxenes have only magnesium and iron as bases.

ORTHORHOMBIC PYROXENES.

ENSTATITE, $MgSiO_3$.

HYPERSTHENE, $(Mg,Fe)SiO_3$.

		$a(b)$		$b(a)$		c
ORTHORHOMBIC, bipyramidal.	Enstatite,	1.0307	:	1	:	0.5885.
	Hypersthene,	1.0319	:	1	:	0.5872.

Twinning: Rare; polysynthetic lamellæ parallel to (014). Also twinning plane (101), crossed twins.

Cleavage: (110) pronounced, also (100) and (010). Fracture uneven. H. = 5–6. Sp. gr. = 3.1–3.3 enstatite, 3.4–3.5 hypersthene.

Optical Properties: biaxial. Axial angle large, varies with content of iron.

Enstatite, (+) $\alpha_y = 1.665$, $\beta_y = 1.669$, $\gamma_y = 1.674$, $\gamma - \alpha = 0.009$, $2V = 70°$.

Hypersthene (−) $\alpha = 1.692$, $\beta = 1.702$, $\gamma = 1.705$, $\gamma - \alpha = 0.013$, $2V = 50°$.

Color: enstatite—grayish, yellowish, greenish white to olive-green and brown. Hypersthene—dark brownish green, grayish, greenish black, brown. Pleochroism more pronounced in darker colored varieties.

Luster: vitreous to pearly on cleavage surfaces, metalloidal in bronzite.

Chemical Composition.—Enstatite and hypersthene are parts of an isomorphous series of magnesium and iron metasilicates. $MgSiO_3$, $(Mg,Fe)SiO_3$. The nearly pure magnesium metasilicate is known as enstatite. But this name is applied to varieties containing ferrous iron, up to about the proportion of MgO:FeO::3:1. When iron is more abundant, from MgO:FeO::3:1 to 1:1, the mineral is hypersthene. For these proportions the composition of pure orthorhombic pyroxenes should be

$MgO \cdot SiO_2 = SiO_2$ 60, MgO 40 = 100.

$3MgO \cdot FeO \cdot 4SiO_2 = SiO_2$ 55.5, MgO 27.7, FeO 16.8 = 100.

$MgO \cdot FeO \cdot 2SiO_2 = SiO_2$ 51.8, MgO 17.2, FeO 31.0 = 100.

Most orthorhombic pyroxenes are intimately associated with monoclinic pyroxenes, being often intergrown in microscopic layers. They also frequently inclose other minerals, so that chemical analyses of the mixtures show variable amounts of alumina and lime, with traces of ferric oxide, titanium oxide, and the alkalies.

Alteration.—Enstatite is not attacked by hydrochloric acid. Hypersthene is partly decomposable. Both minerals alter somewhat more readily than monoclinic pyroxenes. The commonest change is to a fibrous aggregate—bastite—having about the composition of serpentine. The fibers lie parallel to the *c* axis of the pyroxene, and start from cracks and from the surface, chiefly the ends of the crystal. Enstatite sometimes alters to a confused aggregate of serpentine scales or fibers. Less often the change is to talc. Still further alteration leads to the production of quartz, limonite, and carbonates. Hypersthene also alters to fibrous amphibole, uralite, and rarely into compact hornblende.

Crystal Forms.—Enstatite and hypersthene crystallize in orthorhombic forms more or less prismatic with *a*(100), *b*(010), *m*(110), several bipyramids, and sometimes the third pinacoid *c*(001). Figs. 1 (enstatite), 2 (hypersthene). The prism and first and second pinacoids are

usually the best developed, so that cross sections are generally 8-sided, squares formed by (100) (010), with the corners truncated by (110). The bipyramidal planes are seldom sharply defined on rock-making pyroxenes. It is customary to orient orthorhombic crystals so that the *a* axis is shorter than the *b* axis, and in this species the cleavage prism is taken as the unit prism (110). But the frequent parallel growths of orthorhombic and monoclinic pyroxenes show that the shorter, *b*, axis of the monoclinic form is parallel to the shorter axis of the orthorhombic one, the *c* axes in each being parallel to one another, and the longer, *a*, axis in the monoclinic form and the longer lateral axis in the orthorhombic form are in the same plane of symmetry.

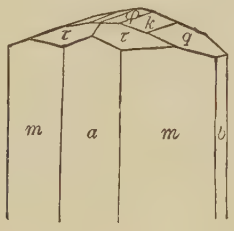

FIG. 1.

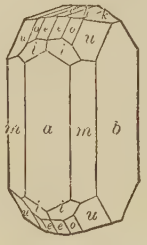

FIG. 2.

That is, the axis usually called *a* in the orthorhombic form is oriented parallel to the *b* axis in the monoclinic form. To maintain the parallelism existing in nature between these forms of pyroxene the orthorhombic crystals should be oriented with the smaller angle between the prism faces in front, *a* should be greater than *b*. For enstatite $a(\breve{b}):b(\breve{a}):c::1.0307:1:0.5885$, and for hypersthene $a(\breve{b}):b(\breve{a}):c::1.0319:1:0.5872$.

Euhedral crystals are usually thick prismatic in habit, the length along the *c* axis being 2 or 3 times the thickness of the prism. Prisms 5 times as long as thick are common as microlites, but long thin prisms of orthorhombic pyroxene are rare. Somewhat rounded forms occur frequently in the porphyries and lavas.

Anhedral crystals of quite irregular shapes occur in the evenly grained rocks, especially pyroxenites, and in rocks with ophitic texture. Where one fills spaces between lime-soda-feldspars it often yields triangular and wedge-shaped sections. When it is inclosed by hornblende or monoclinic pyroxene the forms are generally rounded. Anhedral crystals of enstatite in the granular rocks are sometimes made up of parallel rodlike parts, between which are long cylindrical spaces. These may be occupied by gas or infiltration products.

Twinning is seldom observed in rock-making enstatite and hyper-

sthene. Crossed twins, having (101), customary orientation, as twinning plane, and (010) as the composition plane, sometimes occur in porphyritic rocks. In anhedral pyroxenes in norites and peridotites, and in certain crystalline schists there is a lamellar twinning parallel to (014). This appears to be secondary, resulting from deformation through pressure, as is the case sometimes in monoclinic pyroxene. The plane (014) when the crystal is oriented as in its intergrowth with augite becomes (104) and is approximately parallel to the basal plane (001) in the monoclinic form, along which there is similar lamellar twinning.

Cleavage.—Generally well developed in two planes parallel to (110) with angles of about 88° and 92°. In cross sections this cleavage of nearly 90° is usually noticeable, but in longitudinal sections it is not always present, especially in hypersthene crystals in recent lavas, which are sometimes very free from cleavage cracks.

Another cleavage parallel to (010) is often better developed than the prismatic. It occurs in pyroxenes in the older granular rocks, and divides the pyroxene into plates. When oriented in conformity to augite this pinacoidal cleavage becomes (100) and is parallel to the lamellar cleavage in diallage.

Another pinacoidal cleavage (100), customary orientation, is sometimes developed less distinctly than the other cleavages. All four cleavage planes may be developed in the same crystal. There is in some cases a crude parting across the axis of the prism, but this is not regular enough to be considered cleavage.

Fracture cracks traverse sections of orthorhombic pyroxene at various angles, and have no particular significance.

Optical Properties.—Biaxial with large axial angle, which decreases with increase in iron content. According to the customary orientation of the crystals the optical orientation is $X \parallel a$, $Y \parallel b$, $Z \parallel c$ (Fig. 3). The slowest ray vibrates parallel to the prismatic axis c, the fastest ray vibrates parallel to the shorter lateral axis a. Oriented in conformity to the intergrowth with augite, the positions in enstatite and hypersthene are shown in Figs. 4 and 5. The plane of the optic axes, parallel to (010), customary orientation, is parallel to (100) when oriented as it is intergrown with augite. Owing to variations in the values of α, β, γ, with the chemical composition of the mineral, the acute bisectrix is Z for enstatite, which is therefore optically positive (+), and it is X for hypersthene, which is optically negative (−). It is said that the change of bisectrices, or the passing of $2V$ through 90°, takes place with about 10 per cent

of FeO. This corresponds to a proportion of MgO: FeO: : 6 : 1, approximately. If this is true, then the chemical limits between enstatite and hypersthene must be changed from 3MgO: 1FeO to 6MgO : 1FeO, or there must be enstatites which are optically negative.

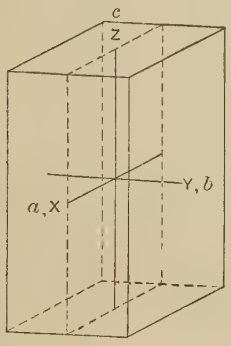

Fig. 3.
Customary orientation.

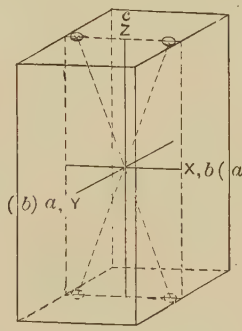

Fig. 4.
Enstatite.

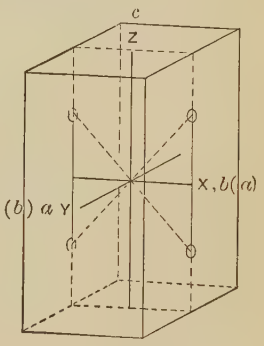

Fig. 5.
Hypersthene.
Oriented as grown with augite.

The following data represent the relation between the optic angle and percentage of FeO in the orthorhombic pyroxenes:

2 *H*, bisectrix *X*.		(FeMn)O.		
133° 8′	r	2.76	Zdjar-Berg, Moravia	Des Cloizeaux
123° 38′	r	5.77	Leiperville, Pa.	"
119°	y	5.71	Fiskernäs, Greenland	Ussing
114° 15′	r	11.14	Njordlersuak, Greenland	Des Cloizeaux
112° 30′	y	8.42	Balsfjord, Norway	Rosenbusch
106° 51′	y	9.86	Kraubat, Steiermark	Tschermak
102°	r	10.62	Lauterbach, Hessen	Des Cloizeaux
98°	y	13.58	Meteorite, Breitenbach	V. v. Lang
98° 22′	r	15.14	Farsund, Norway	Des Cloizeaux
85° 48′	y	18.60	Bodenmais, Bavaria	Becke
85° 39′	r	22.59	Isle St. Paul, Labrador	Des Cloizeaux
84° 18′	y	19.70	Aranyer Berg, Hungary	Krenner
79° 48′	y	27.70	Krakatau	"
59° 20′	y	33.60	Mont Dore, Auvergne	"

The dispersion of the optic axes is slight. From the bisectrix X, $\rho < v$ for the varieties low in iron, $\rho > v$ for varieties richer in iron. The indices of refraction average about the same as those of the monoclinic pyroxenes, but the double refraction is considerably lower, being nearly as low as that of quartz. It is lower in enstatite than in hypersthene.

		α	β	γ	$\gamma-\alpha$	
Enstatite, Zdjar-Berg,		1.656	1.659	1.665	0.009	Mallard
Enstatite, (?)	(y)	1.665	1.669	1.674	0.009	Offret
Bronzite, Kupferberg,	(r)		1.668			Des Cloizeaux
Hypersthene, Farsund,	(r)		1.695			"
Hypersthene, Isle St. Paul,		1.692	1.702	1.705	0.013	Lévy–Lacroix
Hypersthene, "		1.7156		1.727	0.011	Wolff
Hypersthene, Soggendal,			1.7125			Sanger

Zdjar Berg.	Kupferberg.	Lauterbach.	Farsund.	Labrador.	
$2V_r = 69° 42'$	79° 48′	85° 4′	81° 46′	72° 16′	Des Cloizeaux

Color.—Enstatite is the lighter-colored mineral, being yellowish or greenish gray to olive-green and brown. Hypersthene is in darker shades of browns, greens, to black. In thin section the color ranges from colorless through pale yellow, green, and reddish tints to stronger yellow, brown, reds, and green. The more strongly colored varieties rich in iron exhibit noticeable pleochroism from reds and yellows to greens. Some hypersthene with as much as 22 per cent of FeO (Mt. Shasta) exhibits but little color and slight pleochroism in thin sections. The pleochroism increases rapidly with a thickening of the section.

The following colors have been observed in rather thick sections:

Enstatite	Kraubat	*X* greenish yellow	*Y* grass-green	*Z* bluish green	Tschermak
Hypersthene,	Bodenmais	*Y* dark-red brown	*Y* yellow-brown	*Z* dark green	Becke
"	Isle St. Paul	*X* red-brown	*Y* yellowish brown	*Z* green	Lévy and Lacroix
"	"	*X* hyacinth-red	*Y* reddish yellow	*Z* gray-green	Tschermak

In thin sections of the varieties with little iron the colors are: *X* yellowish, *Y* yellowish, *Z* greenish, sometimes with grayish tones. In those rich in iron *X* light red to brownish red, *Y* reddish yellow, *Z* green. The bronze-like luster that characterizes some orthorhombic pyroxene, bronzites, is due to inclusions.

Inclusions.—Of the various kinds of inclusions that occur in these pyroxenes, some are of such frequent occurrence as to be characteristic. They may occur in monoclinic pyroxenes as well, and are not confined to orthorhombic forms. When orthorhombic pyroxenes occur as phenocrysts or as small euhedral and subhedral crystals in porphyries and lavas they may contain inclusions of gas or glass and of magnetite, apatite, zircon, or other minerals that crys-

tallize earlier than the pyroxene. They vary greatly in number in different cases. In some the pyroxenes are almost free from inclusions of any kind; in other cases the inclusions abound.

In coarser-grained rocks the orthorhombic pyroxenes richer in iron, that is, hypersthene and some enstatite, very frequently contain brown to opaque inclusions which appear to be crystals arranged in definite positions in the pyroxene. These microscopic crystals are plates, rods, and minute grains. The plates are six-sided, often elongated in one direction and grading into blades or rods. They are arranged with the plates parallel to (010), customary orientation, which is the plane of principal pinacoidal cleavage. The rod-like forms lie in three directions, one of which is at right angles to the *c* axis of the pyroxene. The nature of these inclusions is not definitely known. The presence of TiO_2 in some analyses of hypersthene has suggested the presence of brookite, but it is more probable that they are ilmenite or titaniferous magnetite, both of which are brown when sufficiently thin. These inclusions exhibit metallic to submetallic luster, and light reflected from them often shows interference colors. This produces the *schiller* seen in bronzite and hypersthene. Such inclusions are in some cases uniformly distributed through the pyroxene, in other cases they are localized or irregularly distributed. Their origin has been variously explained. They are undoubtedly primary in most cases, that is, the microscopic plates, rods, and dots crystallized at the time the pyroxene crystallized orienting themselves with respect to certain directions in the pyroxene. This is clearly indicated by their occurrence in rocks without signs of secondary changes or metamorphism, and by their independence of cracks or fracture planes in the pyroxene.

There are cases, however, in which secondary action has deposited brown inclusions along cracks or in the vicinity of cracks, and especially in the plane of pronounced cleavage (010). But these are much less frequent than the sharply defined inclusions just described, which occur not only in orthorhombic pyroxene, but in some monoclinic forms, and also in lime-soda-feldspars in basic rocks. They are more common in the minerals of those rocks in which iron and titanium are more abundant.

Another characteristic form of inclusion is the lamellar intergrowth of monoclinic pyroxene in thin layers parallel to the plane of pronounced pinacoidal cleavage (010), or sometimes parallel to (110). The two forms of pyroxene are oriented parallel to one another

so far as the *c* axes are concerned. The *b* axis of the monoclinic form is parallel to the shorter axis *a* of the orthorhombic form. The prismatic cleavages are approximately parallel in both forms. Sections cut parallel to the second pinacoid (010) of the monoclinic form are striped by lamellæ which yield alternately parallel and inclined extinction. From the orthorhombic lamellæ there emerges the bisectrix *X*. This lamellar structure may be so thin as to be scarcely perceptible microscopically. It is not visible in sections cut parallel to the lamellæ. It occurs in proxenes in the evenly granular to coarse-grained rocks, and is not known in those of porphyries and lavas. Enstatite in granular rocks sometimes contains long cylindrical spaces parallel to the *c* axis, which may be occupied by gas, or by secondary material which has filtered in.

Modes of Occurrence.—Orthorhombic pyroxenes are common constituents of igneous rocks, and to a lesser extent of metamorphic rocks. They are most abundant in certain pyroxenites, peridotites, and norites; are also found in diorites, and to a much less extent in granites and syenites. They occur in the porphyry and lava equivalents of the rocks just named. They do not occur in rocks containing nephelite or leucite so far as at present known.

Orthorhombic pyroxenes occur in altered and metamorphosed forms of igneous rocks, such as certain serpentines, orthogneisses, and granulites. In rocks metamorphosed from sedimentary deposits they are not so common; and when present it is oftener the less ferrous variety, enstatite. Enstatite also occurs in meteorites in radiating aggregates called chondrules.

Resemblances.—Orthorhombic pyroxenes are most like the monoclinic pyroxenes, from which they are often with difficulty distinguished, having the same shapes in cross sections and nearly the same in longitudinal sections. They are recognized by somewhat lower interference colors, by extinction parallel to the *c* axis in all longitudinal sections, whereas in monoclinic pyroxenes this is only the case in sections parallel to (100). In orthorhombic forms the bisectrix *Z* emerges in the center of sections at right angles to the prism, and the trace of the plane of the optic axes is parallel to the shorter diagonal of the cleavage prism. Hypersthene is generally recognizable by its characteristic colors, light red and green. The orthorhombic pyroxenes are often less cleaved and cracked than the monoclinic ones. When partly altered to bastite they may be identified by this characteristic mode of alteration.

From olivine they may be distinguished by lower double refraction and by pyroxene cleavage; from melilite by the characteristic double

refraction of this mineral. From sillimanite they are distinguished by their lower double refraction and the pyroxene cleavage.

Laboratory Production.—Enstatite fuses at a high temperature, hypersthene at a somewhat lower temperature. They have both been produced by fusion of their constituents in an open crucible.

MONOCLINIC PYROXENES.

COMPOSITION:

Diopside,	$Ca(Mg,Fe)(SiO_3)_2$.
Hedenbergite,	$CaFe(SiO_3)_2$.
Schefferite,	$(Ca,Mg)(Fe,Mn)(SiO_3)_2$.
Augite,	$m[Ca(Mg,Fe)(SiO_3)_2]$, $n[(Mg,Fe)(Al,Fe)_2(Si,Ti)O_6]$, sometimes $Na(Al,Fe)(SiO_3)_2$.
Acmite,	$Na^{III}Fe(SiO_3)_2$.
Jadeite,	$NaAl(SiO_3)_2$.

MONOCLINIC; prismatic class, in part domal (?). Diopside, augite, $a:b:c = 1.09213:1:0.58932$, $\beta = 74° 10' 9''$.

Acmite, $a:b:c = 1\ 0996:1:0.6012$, $\beta = 73° 11'$.

Jadeite, in good microscopic crystals evidently monoclinic.

Twinning: common twinning plane (100), also lamellar parallel to (001); rarely cruciform twins, (101); and contact and cruciform twins, ($\bar{1}22$).

Cleavage: (110) sometimes rather perfect; (100) not so common, sometimes well developed; (001) parting parallel to twin lamellæ occasionally pronounced. Fracture uneven to conchoidal. H.: diopside, augite 5–6, acmite 6–6.5, jadeite 6.5–7. Specific gravity = 3.2–3.6 according to composition.

OPTICAL PROPERTIES.—Biaxial. Plane of the optic axes parallel to (010) Axial angle and inclination of the bisectrices to the crystal axis c vary with the chemical composition of the pyroxene.

	α_γ	β_γ	γ_γ	$\gamma - \alpha$	
Diopside	1.6710	1.6780	1.7000	0.0290	$2V = 58° 43'$
"	1.6986	1.7057	1.7271	0.0285	$2V = 60° 28'$
Hedenbergite	1.7320	1 7366	1.7506	0.0186	$2V = 59° 52'$
Augite	1.712	1.717	1.733	0.021	
Acmite (ægirite)	1.7630	1.7990	1.8126	0.0496	$2V = 62° 13'$
Jadeite				0.029	

Color: colorless, white, greenish through various shades of green to black, sometimes brownish In thin section colorless, greenish to green, yellowish to purplish brown in titaniferous varieties, slightly pleochroic in some augites to strongly pleochroic in ægirite and augite, when it is brown and green. Luster vitreous, inclining to resinous.

Chemical Composition.—The monoclinic pyroxenes, diopside, augite, augite-ægirite, acmite (ægirite), are members of an isomorphous series, which contains also the rare mineral jadeite. They are known to grade into one another through slight modifications in the chemical composition of concentric zones in single crystals. They are metasilicates of calcium, magnesium, and iron, in diopside; with some aluminium and ferric iron and a little sodium, in augite. With increase of sodium and ferric iron there is a transition to acmite, which is metasilicate of sodium and ferric iron. It is possible that the jadeite molecule occurs in some augites to a greater extent than is indicated by the analyses so far made. Jadeite occurs by itself in certain rare rock masses.

It is to be noted that in ideal diopside, free from aluminium, there is a constant molecular ratio between CaO and (Mg,Fe)O, which is 1:1. But the ratio between MgO and FeO is variable, MgO commonly being in excess. With excess of FeO the mineral is called hedenbergite. Small amounts of $(Al,Fe)_2O_3$ occur in crystals called diopside, augite having 3 per cent and more of Al_2O_3, the maximum being about 10 per cent. Similarly small amounts of Na_2O and K_2O occur in most augites. When Na_2O exceeds about 2.50 per cent the pyroxene generally has sufficient acmite molecules to affect the color, and the mineral is called ægirite-augite. With abundant Na_2O and Fe_2O_3 and little CaO, MgO, and Al_2O_3, it is ægirite. Ideally pure acmite is rare, like pure diopside.

The accompanying table of analyses shows the variations in composition of monoclinic pyroxenes and the kind of rocks in which they occur. A few only of metamorphic origin are given, which will be referred to in another connection. The list of those from igneous rocks shows that there is no simple relation between the composition of the monoclinic pyroxenes and the kind of magma out of which they crystallize. However, a complex relationship will be found to exist.

Diopsides with little or no alumina occur in such widely different rocks as the leucite-lavas of Leucite Hills, Wyo.; granite of Laveline, Vosges; certain gabbros, basalts, pyroxenites, and picrites. The reason for the absence of alumina from the pyroxenes in these rocks is to be sought in the relatively low alumina in the magmas, the alumina present entering alkalic aluminous minerals and anorthite. In the interpretation of the alumina content of magnesian minerals and rocks caution is necessary owing to the possibility of error in the determination of alumina in the presence of mag-

nesia, the latter being sometimes precipitated in part with the alumina.

Augites with various amounts of alumina occur in gabbros and basalts of various compositions. In some cases high alumina in the augite corresponds to relatively high alumina in the rock magma. In others the rock magmas are low in alumina, but also low in alkalies. So that it appears that the percentage of alumina in the augite depends on the available alumina in the rock magma, after the alkalies have been satisfied; the amount of alumina entering into anorthite feldspar molecules being proportionately greater as compared with the normative anorthite the greater the amount of albite molecules with which they may combine. Otherwise there appears to be little relationship between the amount of alumina in the augite and the kind of rock in which it occurs, judging by the names given in the accompanying list.

Soda-bearing pyroxenes, ægirite-augite, ægirite and acmite, crystallize from magmas rich in soda, and in which alumina is lower than the alkalies or nearly equal to them molecularly. They occur in nephelite-syenites, phonolites, tinguaites, some soda-granites, and related rocks.

Alteration.—The monoclinic pyroxenes are not decomposed by acids except hydrofluoric, or are but slightly attacked. In rocks they are found to be less readily altered than orthorhombic pyroxenes. The processes of alteration vary with the composition of the pyroxene and with other conditions.

Diopsides in metamorphic rocks frequently change to talc or serpentine, sometimes with the production of epidote. They may also alter to amphibole, tremolite, or actinolite, usually fibrous. In igneous rocks diopside, whether as malacolite, salite, diallage, or omphacite, alters in a similar manner; commonly to serpentine, which appears as scales or fibers starting from cracks and the surface of crystals, generally accompanied by carbonates, probably calcite for the most part, and in some cases by epidote. In varieties containing alumina chlorite may be developed upon alteration as in augite. The alteration to more or less fibrous amphibole, uralite, is common.

Augite in igneous rocks usually alters to chlorite, which forms aggregations of scales and fibers without definite arrangement in most cases. This may be accompanied by epidote, carbonates, mostly calcite, and quartz, and may eventually result in carbonates, limonite, kaolin, and quartz. The change to uralite is common, and in

CHEMICAL ANALYSES OF MONOCLINIC PYROXENES.

ROCK. LOCALITY.	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O	TiO_2	Cr_2O_3	MnO	Total
Diopside.													
1. Wyomingite, Leucite Hills, Wyo.	50.86	—	1.19	1.82	17.42	23.32	0.76	0.42	0.31	3.03	—	0.03	99.16
2. Granite, Laveline, Vosges	50.63	0.87	3.33	8.39	13.01	21.30	1.02	0.50	—	0.79	—	—	99.84
3. Gabbro, Loch Scavaig, Skye	49.27	0.22	2.17	12.15	14.81	20.26	—	—	0.72	—	—	0.38	99.98
4. Gabbro, Le Prese, Veltlin	51.46	1.31	—	15.94	10.13	21.14	—	—	—	—	—	—	99.58
5. Basalt(?), Bozeman Creek, Mont.	52.50	2.26	2.05	2.47	17.11	21.70	0.35	0.07	0.64	—	1.07	tr.	100.32
6. Olivine nodules in basalt, Lausitz	53.08	1.44	—	6.05	17.05	22.34	—	—	—	—	tr.	—	99.96
7. Basalt, Jan Mayen	51.86	1.56	2.44	3.46	17.40	22.15	—	—	0.12	—	0.73	—	199.72
8. Pyroxenite, Kremze, Bohemia	53.67	2.45	2.07	3.84	13.57	20.34	1.29	1.48	—	—	1.49	—	100.20
9. Websterite, Hebbville, Md.	51.80	2.21	1.29	3.50	17.76	20.99	—	—	0.65	0.13	0.51	tr.	98.84
10. Picrite, Schwarzenstein, Fichtel-Gebirge	52.63	2.24	—	6.84	17.30	20.04	—	—	0.57	—	0.72	—	100.34
Augite.													
11. Dolerite, Londorf, Hessen.	48.74	2.82	—	12.36	15.27	16.55	—	—	0.10	3.35	—	—	99.19
12. Gabbro, Harzburg	52.34	3.05	—	8.84	15.58	19.18	—	—	0.66	—	—	—	99.65
13. Syenitic lamprophyre(?), Two Buttes, Colo.	51.27	3.05	3.08	4.34	14.21	22.58	0.67	0.06	—	0.70	NiO 0.03	0.28	100.27
14. Gabbro, Rum	50.54	3.35	1.34	4.42	17.05	21.42	0.53	0.25	0.71	—	—	0.23	99.84
15. Leucite-basalt(?), Laacher See	50.03	3.72	2.36	6.65	13.48	22.85	—	—	—	—	—	0.15	99.24
16. Diabase, Whin Sill, Tyne Head	48.41	4.05	2.36	15.08	12.14	15.98	—	—	1.19	—	—	0.37	99.58
17. Lherzolite, Pyrenees	53.63	4.07	—	8.52	12.48	20.37	—	—	—	—	1.30	—	100.37
18. Tinguaite (?), Two Buttes, Colo.	47.54	4.14	5.64	6.42	10.05	21.57	1.38	0.12	—	3.00	tr.?	0.36	100.21
19. Monzonite, Monzoni	49.60	4.16	—	9.82	14.42	21.86	—	—	—	—	—	—	99.86
20. Shonkinite, Square Butte, Mont.	49.42	4.28	2.86	5.56	13.58	22.35	1.04	0.38	0.09	0.55	—	0.10	100.21
21. Gabbro, Gwynne Falls, Md.	51.41	4.32	—	9.31	15.14	20.60	—	—	—	—	—	0.04	100.82
22. Lava, 1858, Vesuvius	49.61	4.42	—	9.08	14.22	22.83	—	—	—	—	—	—	100.16
23. Melaphyre, Fassathal	49.01	5.09	3.77	7.74	14.55	20.01	—	—	—	—	—	—	100.17
24. Alnöite, Alnö	50.05	5.15	4.98	3.14	13.02	23.46	—	—	—	—	—	—	99.80
25. Minette, Weissenburg	48.23	5.28	4.83	5.01	15.84	19.85	0.67	0.52	0.45	—	—	—	100.68
26. Gabbro, Wiesenthal, Baden	51.34	5.35	0.48	4.42	14.08	21.12	0.84	0.15	0.70	0.58	0.43	—	99.49
27. Basalt, Monti Rossi, Etna	47.38	5.52	3.85	7.89	15.26	19.10	—	—	0.43	—	—	0.10	99.53
28. Tephrite, Sonnenberge, Baden	47.20	5.80	3.17	4.76	12.79	23.02	—	—	—	2.70	—	—	99.44
29. Analcite-basalt, The Basin, Colo.	49.26	6.01	3.31	4.23	12.40	21.79	0.79	0.4	—	1.53	—	SrO 0.06	99.79

Rock. Locality.	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O	TiO_2	Cr_2O_3	MnO	Total
Augite (Continued).													
30. Olivine-gabbro, Coverack, Cornwall	49.9	6.2	1.7	3.9	16.1	20.4	—	—	0.9	—	0.6	0.4	100.1
31. Nephelite-basalt, Oberleinleiter	46.48	6.24	5.88	4.42	13.51	23.45	—	—	0.20	—	—	tr.	100.18
32. Diabase, Sugar Loaf, Colo.	47.32	6.37	2.56	14.40	13.43	16.08	—	—	—	—	—	—	100.16
33. Eukrite, Store Bekku fjord, Norway	47.67	6.46	7.95	1.47	13.38	20.15	—	—	0.64	2.78	tr.	—	100.50
33*a*. Leucitite, Ticchiena, Italy	45.46	5.47	6.62	5.64	11.72	20.17	0.72	0.65	—	2.85	—	0.15	100.45
34. Limburgite, Limburg	44.65	6.62	5.02	3.87	14.76	20.32	1.29	0.49	—	2.93	—	—	99.95
35. Limburgite, Reichenweiher, Elsass	46.72	6.90	3.31	3.30	16.10	21.36	0.87	0.82	—	—	—	—	99.38
36. Leucitophyre, Koschkserai, Marand, Persia	49.62	7.27	2.22	4.43	13.06	22.14	0.50	0.80	0.70	—	—	—	100.74
37. Haüynophyre, Melfi, Italy	44.55	7.27	6.06	5.91	10.44	22.83	1.47	0.52	—	1.36	—	—	100.41
38. Tephrite, Kaiserstuhl	45.83	7.47	4.90	4.11	10.92	22.83	—	—	—	3.57	—	—	99.63
39. Nephelite-basalt, Black Mt., Uvalde, Texas	45.23	7.73	2.95	4.07	12.25	23.37	0.47	0.12	0.37	4.28	NiO 0.05	0.07	100.96
40. Basalt, Mt. Taylor region, New Mexico	47.06	7.77	1.30	8.15	13.52	19.33	0.33	0.11	0.20	1.82	tr.	0.20	99.85 $+P_2O_5$ 0.06
41. Monchiquite, Rio do Ouro, Rio Janeiro	44.55	7.86	3.81	4.53	12.71	20.84	1.29	0.49	—	2.85	—	0.38	99.31
42. Dolerite, Valmont, Colo.	49.10	7.95	—	8.30	12.37	22.54	tr.	tr.	—	—	—	—	100.26
43. Haüynophyre, Kaiserstuhl	46.54	8.20	3.72	4.32	13.19	21.29	—	—	—	2.85	—	—	100.11
44. Lava, 1631, Vesuvius	48.86	8.63	2.73	4.54	14.01	20.62	—	—	—	—	—	—	99.39
45. Leucite-tephrite, Tetschen	45.67	9.04	7.46	2.00	12.09	21.78	1.25	0.56	0.31	0.62	—	—	100.78
46. Hypersthene-diabase, The Twins, Va.	49.33	9.15	0.27	9.05	14.58	16.36	0.55	0.19	0.25	—	—	—	99.73
Ægirite-augite and ægirite.													
47. Phonolite, Oberschaffhausen, Baden	49.75	0.53	13.23	9.66	4.55	16.72	2.26	—	—	1.45	—	1.09	99.24
48. Laurvikite, Laurvik, Norway	50.33	0.30	—	12.37	10.98	22.01	2.14	0.94	—	0.66	—	—	99.73
49. Nephelite-basalt, Katzenbuckel	52.20	2.36	8.51	none	12.83	18.42	2.56	0.78	—	3.12	—	0.12	100.90
50. Granite, Kekequabic, Minn.	53.19	2.38	9.25	5.15	9.43	17.81	2.63	0.38	0.01	—	—	—	100.23
51. Leucitophyre, Burgberg, Rieden	46.47	4.28	5.95	12.17	7.24	19.23	2.61	0.74	—	0.73	—	—	99.42
52. " " "	45.80	2.80	11.11	7.41	6.63	20.06	2.88	1.00	—	0.52	—	0.27	98.48
53. Nephelite-basalt, Katzenbuckel	52.57	1.33	5.86	3.23	12.36	18.49	3.80	1.03	—	2.18	—	0.15	101.00
54. Nephelite-syenite, Zwart Koppies, S. Africa	46.72	2.41	17.29	10.57	2.57	13.51	4.88	0.48	—	tr.	—	1.31	99.74
55. Nephelite-syenite, Serra de Monchique, Portugal	42.27	8.67	13.93	6.24	10.95	12.32	3.66	2.12	—	0.92	—	—	101.08
56. Nephelite-syenite, Särna, Dalekarlien	49.32	4.88	16.28	5.65	4.28	9.39	8.68	0.68	—	1.25	—	—	100.41

CHEMICAL ANALYSES OF MONOCLINIC PYROXENES.

ROCK.	LOCALITY.	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O	TiO_2	Cr_2O_3	MnO	Total
Ægirite-augite and ægirite (Continued).														
57. Nephelite-syenite,	Barreros, Sao Paulo, Brazil	51.60	1.92	26.29	4.20	1.15	4.25	8.89	1.05	0.56	—	—	—	99.91
58. Phonolite,	Hohentwiel	42.15	5.17	16.86	8.54	3.56	10.39	10.69	2.64	—	tr.	—	tr.	100.00
59. Nephelite-syenite,	Brevik	51.74	0.47	26.17	3.48	1.79	5.07	11.02	0.34	—	—	—	1.79	100.54
60. Nephelite-syenite,	Lujavr Urt, Kola	51.82	0.60	21.02	8.14	1.47	3.01	11.87	0.85	0.50	—	—	1.00	100.28
61. Nephelite-syenite,	Magnet Cove, Ark.	51.41	1.82	23.30	9.45	0.31	2.03	11.88	tr.	—	0.13	—	—	100.33
Acmite.														
62. Acmite-granite,	Rundemyr, Eker, Norway	51.66	—	28.28	5.23	—	—	12.46	0.43	0.39	1.11	—	0.69	100.25
Theoretical composition,	$NaFe(SiO_3)_2$	52.0	—	34.6	—	—	—	13.4	—	—	—	—	—	100.0
Diopside.														
63. Serpentine,	Ala, Italy	54.74	—	—	2.91	17.02	26.03	—	—	—	—	—	—	100.70
64. Iron ore,	Taberg, Sweden	53.71	0.40	0.88	2.94	15.67	25.09	—	—	0.30	—	—	0.20	99.19
65. Limestone nodules,	Vesuvius	53.2	1.5	—	2.3	19.3	23.4	—	—	0.2	—	—	—	99.9
66. Crystalline limestone,	De Kalb, N. Y.	55.12	0.40	—	1.12	18.15	25.04	0.45	0.02	0.17	—	—	—	100.47
67. Magnetite,	Nordmark, Sweden, V.	54.59	—	0.11	2.49	17.42	25.70	—	—	—	—	—	0.14	100.45
68. "	" " IV.	54.09	0.28	0.19	3.36	17.12	25.41	—	—	—	—	—	0.26	100.71
69. "	" " III.	54.26	0.33	0.48	3.51	16.04	24.82	—	—	—	—	—	0.45	99.89
70. "	" " II.	53.03	0.75	0.32	7.34	13.65	22.98	—	—	—	—	—	1.13	99.20
71. "	" " I.	50.91	0.17	0.76	17.34	7.21	22.93	—	—	—	—	—	0.21	99.53
72. Marble,	Tunaberg, Sweden	49.01	—	—	26.08	2.98	20.87	—	—	—	—	—	—	98.94
Augite.														
73. Limestone nodules,	Vesuvius	51.01	4.84	3.51	3.16	16.58	20.80	—	—	—	—	—	—	99.90
74. "	" "	50.41	6.07	1.09	6.78	12.92	22.75	—	—	—	—	—	—	100.02
75. "	" "	46.95	9.75	4.47	4 09	16.04	19.02	—	—	—	—	—	—	100.32
76. Metamorphosed limestone,	Fassathal.....	44.76	10.10	5.01	2.09	13.65	24.90	—	—	—	—	—	—	100.51

some cases the hornblende is compact, when its secondary nature is determined either by its having the external crystal form of pyroxene, or by its extending in secondary veins across other minerals, such as feldspars; otherwise it may be easily confused with primary compact hornblende surrounding pyroxene. The complete removal and replacement of augite by opal occurs in some lavas that have been acted on by hot vapors or strong acids.

Aegirite-augite, *ægirite*, and *acmite* are not well known in an altered condition. It may be assumed that as the composition approaches augite the alteration products are nearly the same as those of augite Ægirite generally appears quite fresh. Brögger has noted in one instance its alteration to analcite. J. Francis Williams has suggested that at Magnet Cove, Ark., manganpectolite has developed from ægirite.

Jadeite is known to change by processes of metamorphism to nephrite, that is, tremolite, in the form of dense aggregates of minute scales and fibers.

Crystal Forms.—The monoclinic pyroxenes—diopside, augite, ægirite, acmite, and probably jadeite—are closely isomorphous, but differ somewhat in the commoner types of habit which they assume. They appear to belong to the prismatic class of the monoclinic system, but may in part belong to the domal, which is suggested by exceptional crystals from Canaan, Conn., and Orange County, N. Y. However, the common forms exhibit the higher degree of symmetry, as do also the etched forms on (100), (010), (110). (Fig. 6.) These etched figures serve to identify the particular pinacoidal and pris-

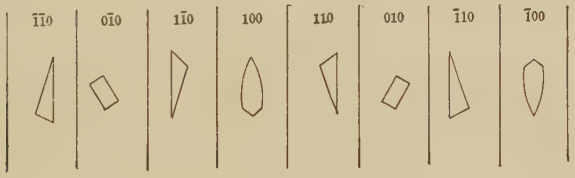

FIG. 6.

matic planes by the shape and orientation of the figure on each as shown in the diagram.

Diopside-augite, $a:b:c=1.09213:1:0.5832$, $\beta=74°\ 10'\ 9''$.
Acmite, $a:b:c=1.0996:1:0.6012$, $\beta=73°\ 11'$.

In general the habit of diopside and augite crystals is that of short, thick, prisms sometimes several times longer than thick. It is rarely tabular or bladed, though these shapes occur oftener in

crystals in metamorphosed limestones and in those grown freely in cavities. On the other hand the more alkalic pyroxenes—ægirite, acmite, and also the rare jadeite—more frequently develop long prismatic crystals.

In *diopside* and *augite* the common forms are: $a(100)$, $b(010)$, $c(001)$, $m(110)$, $n(\bar{2}21)$, $p(\bar{1}01)$, and $s(\bar{1}11)$ in augite. Some of the simpler types of diopside are shown in Figs. 7, 8, and 9, while those of augite are Figs. 10, 11. When in igneous rocks, in some cases

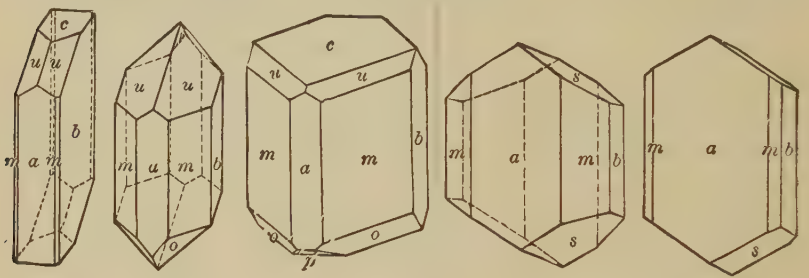

FIG. 7. FIG. 8. FIG. 9. FIG. 10. FIG. 11.

the first and second pinacoids, (100), (010), are strongly developed with quite subordinate prism faces (110). Cross sections of such crystals are nearly square with truncated corners. In other crystals the prisms (110) are nearly as well developed as the pinacoids, and the cross sections are almost octagons. It less frequently happens that the prism faces are larger than the pinacoids. Cross sections of pyroxenes are quite characteristic, owing to the habit just mentioned and the fact that the angle between the prism faces is nearly 90°. $110 \wedge 1\bar{1}0 = 92° 50'$ (Fig. 12). Longitudinal sections are sometimes terminated by edges symmetrical to the longer diameter of the section, as in orthorhombic pyroxene—sections at right angles to the plane of symmetry—but more frequently they are terminated by edges inclined unsymmetrically to the direction of the c axis—sections parallel to (010), or nearly so.

In *ægirite* and *acmite* the habit is more frequently that of long thin prisms with steeper terminal planes $O(\bar{6}61)$ (Figs. 13 and 14). The first pinacoid, $a(100)$, and the prism faces $m(110)$ are usually well developed, while the second pinacoid, $b(010)$, may be wanting or very small. Cross sections of such crystals are generally six-sided (Fig. 15) and resemble somewhat those of amphibole, from which they are distinguished by the prismatic angle. These cross sections are characteristic of ægirite and acmite.

Jadeite crystals are also long prisms in some instances with six-sided cross sections bounded by $a(100)$ and $m(110)$, like those of ægirite.

In the igneous rocks *euhedral* crystals of monoclinic pyroxenes occur as phenocrysts in porphyritic rocks and as crystals in a glass base or groundmass. In the larger crystals the terminal faces are often well developed and recognizable, but in the smaller ones they are not so sharply developed.

Subhedral crystals are more common, the planes in the prism zone being distinct, while those at the extremity of the prism are

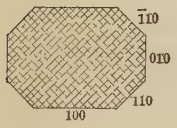

Fig. 12.

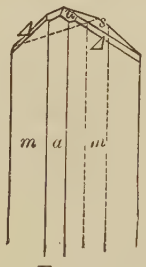

Fig. 13.
Ægirite.

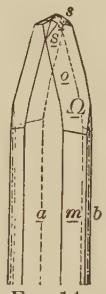

Fig. 14.
Acmite.

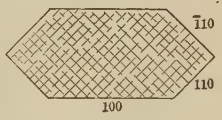

Fig. 15.

not recognizable. More or less rounded forms occur, and those whose growth was interfered with by adjacent crystals. Abnormal forms occur as microlites in some rock glasses, called "crippled" crystals by Zirkel. They are in some cases knobbed at the ends of short prisms.

Rarely they form curved and radiating aggregates, as in the glassy basalt from Mauna Loa, Hawaii, Fig. 16; or feather-like and plumose groups of microlites, as in the pitchstone of Arran, Fig. 17. In this rock there are also rectangular branching aggregates of pyroxene needles.

Anhedral forms with nearly equidimensional shapes occur in granular rocks, like pyroxenite and some gabbros; or they may have still more irregular shapes, as when they form the matrix mineral for lime-soda-feldspars in some basalts with ophitic fabric.

Twinning.—1. The commonest law is that in which the twinning plane and composition plane is (100). The usual form in augite is shown in Fig. 18. Often between the two principal twinned parts there are one or more thin lamellæ in twinned position. This form of twinning in general only affects the outline of sections cut parallel

to (010) or nearly so, and may be overlooked in other sections, but it is easily recognized by the optical orientation of the twinned parts

Fig. 16.

when seen between crossed nicols. It will not show itself in sections cut parallel to (100). 2. Twinning and composition plane (001).

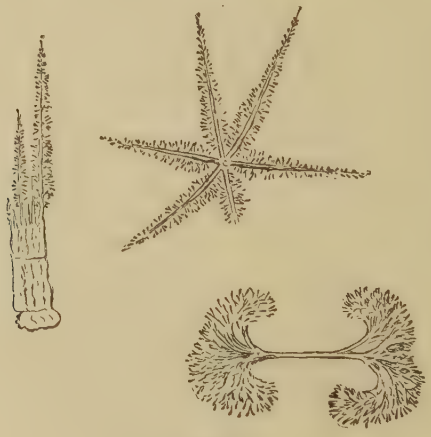

Fig. 17.

This is usually repeated in thin plates or lamellæ and is not noticeable in the outline of the crystal, but in the optical orientation of the

lamellæ, which are often separated by planes of parting. This twinning is of secondary origin in many cases, being produced by pressure. It has been produced in this manner artificially. It is absent from pyroxenes in unaltered lava forms of igneous rocks. 3. A third mode of twinning is on (101), resulting in cruciform twins, Fig. 19. 4. Still another twinning is on the plane ($\bar{1}22$), and may sometimes be repeated several times, forming a stellate group. These last two modes of twinning are rare, but have been observed on augite in basalt from Bohemia.

Cleavage parallel to (110) is often well developed and especially noticeable in thin section, but is sometimes quite imperfect. In cross sections the traces of this cleavage intersect at 92° 50′ (Fig. 12).

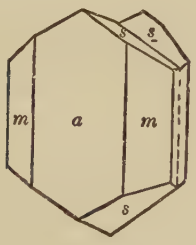

Fig. 18.

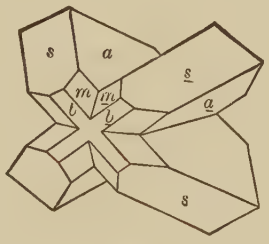

Fig. 19.

A second cleavage parallel to (100) is highly developed in some diopsides and augites, which are then called diallage. The crystals separate into thin plates. This may be imperfectly developed in other cases and may be accompanied by an imperfect cleavage parallel to (010). In such cases cross sections exhibit cleavage lines in two rectangular sets intersecting one another symmetrically. In longitudinal sections the traces of all of these cleavages are parallel to one another, but they seldom extend as uninterrupted cracks the full length of the crystal, being usually short and interrupted.

A parting parallel to (001) is generally well developed in crystals twinned in lamellæ parallel to this plane. It appears to be a result of the multiple twinning, and is not true cleavage. *Fracture*, uneven to conchoidal, shows itself in thin section as irregular cracks traversing the crystal in any direction.

H. = 5–6, diopside, augite; 6–6.5, acmite; 6.5–7, jadeite.

The specific gravity varies with the chemical composition, being highest in the pyroxenes richest in iron.

Fassaite,	2.979	Fassathal		
Diopside,	3.11	Zermatt	3.287	Dekalb, N. Y.
Hedenbergite,	3.311	Nordmark	3.588	Dognacska
Augite,	3.233	Vesuvius	3.434	Rossberg
Ægirite,	3.51	Kola Peninsula	3.63	Kangerdluarsuk
Acmite	3.520	Rundemyr		
Jadeite,	3.27	Burma	3.346	Burma

Optical Properties.—In the monoclinic pyroxenes, including jadeite, the plane of the optic axes is parallel to the second pinacoid (010), the plane of symmetry. The acute bisectrix Z is situated in the obtuse angle β, between the crystal axes c and a, and the inclination of the bisectrices to the crystal axis c and the value of the angle between the optic axes vary with the composition of the pyroxene. But the chemical composition being complex, no simple relationship between it and the optical properties has been discovered up to the present, and the data already collected on these characters are quite incomplete.

A study of the diopside-hedenbergite series shows that the inclination of the acute bisectrix Z to the crystal axis c increases with the content of iron, but not in a simple ratio, as the following data indicate:

	$Z \wedge c$.	Fe_2O_3.	FeO.	Analysis in Table.	
Diopside, Nordmark, type V	38° 3½′	0.11	2.49	(67)	Flink
" Ala.	38° 41½′	—	2.91	(63)	Wülfing
" "	38° 54′				Des Cloizeaux
" Nordmark, type IV	38° 45′	0.19	3.36	(68)	Flink
" " " III	39° 1′	0.48	3.51	(69)	"
" Taberg	41° 24′	0.88	2.94	(64)	G. Nordenskiöld
" Nordmark, type II	41° 41′	0.32	7.34	(70)	Flink
" " " I	44° 38½′	0.76	17.34	(71)	"
Hedenbergite, Tunaberg	47° 10′	—	26.08	(72)	Wülfing

The data with respect to the diopside-augite and augite-ægirite series is not so definite, the variations in composition being greater. The inclination of the acute bisectrix Z to the crystal axis c in the diopside-augite series, as observed by Herwig and also by Doelter, ranges from 38°, in varieties near diopside, to 52° in augites richer in Al_2O_3 and Fe_2O_3. In jadeite the angle of inclination ranges from 31° to 45°. Further, it is known that there is a gradation of properties from augite to ægirite and acmite, and that in the latter pyroxenes the angle $Z \wedge c$ is greater than 90°, the acute bisectrix X lying in the obtuse angle β and making an angle of from 3½° to 6° with c. Observations on the inclination of X to c are as follows:

		$X \wedge c$.	
Ægirite	Langesund	$2\frac{1}{2}°_y$ to $3\frac{1}{2}°_y$	Brögger
		$4°_y$ to $4°\ 15'_y$	Wülfing
"	Kola	$4°_w$ to $5°_w$	Ramsay (white light)
Acmite	Rundemyr	$5\frac{1}{2}°$ to $6°$	Brögger

The accompanying diagram, Fig. 20, represents the position of the bisectrices in the plane of (010) for different kinds of monoclinic pyroxenes, corresponding to the data given. It will be seen that the angle $Z \wedge c$ increases with increase of iron from about 38° to 96°. The angles $X \wedge c$ decrease correspondingly from 52° to 0° and 6° in the obtuse angle β. If one considers the extinction angles measured from c in the plane (010) without regard to the character of the bisectrix, it will be found that angles from 38° to 45° correspond to diopside and augite, while angles from 38° to 6° are those of ægirite-augite; ægirite-acmite having angles from 6° to 0°, to 6° on either side of c.

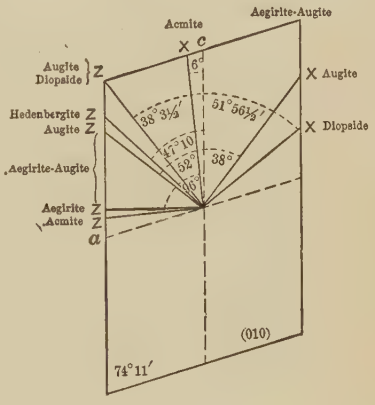

Fig. 20.

The optic angle is large in all varieties of monoclinic pyroxenes, increasing slightly with the content of iron. In diopside, augite, and jadeite the acute bisectrix is Z; they are optically (+). In ægirite and acmite the acute bisectrix is X; optically (−). The optic angle is 90° for some intermediate ægirite-augite, not yet fully investigated.

There is a dispersion of the bisectrices within the plane of symmetry, yielding inclined dispersion. It is slight in diopside, but is strong in certain titanium-bearing augites, and is also considerable in ægirite. In this mineral the dispersion of the bisectrices is about $1\frac{1}{2}°$. $X \wedge c = 3°\ 30'_r$ and $4°\ 58'_{gr}$. From this it happens that in sections of ægirite and titaniferous augites cut parallel to (010) light is not extinguished completely between crossed nicols in any position, and if the section is rotated from a position of maximum darkness to one side it becomes yellow, to the other side blue; the direction of rotation necessary to produce either color depending on the orientation of the section with respect to the axis of rotation. A similar phenomenon is also visible in sections cut nearly

perpendicular to an optic axis in titaniferous augite, owing to a strong dispersion of the optic axes, which is $\rho < v$ about Z.

	Anal.	α	β	γ	$\gamma-\alpha$	$2V$	
Diopside, Ala.	(64)	1.6727_y	1.6798_y	1.7026_y	0.0299	58° 59′$_y$	Des Cloizeaux
" "	(64)	1.6707_D	1.6776_D	1.6996_D	0.0289	59° 9′	Dufet
" Nordmark, V	(67)	1.6710_y	1.6780_y	1.7000_y	0.0290	58° 43′	Wülfing
" " IV	(68)	1.6734_y	1.6804_y	1.7029_y	0.0295	58° 57′	Wülfing
" Taberg	(65)	1.6765_y	1.6836_y	1.7052_y	0.0267	59° 22′	G. Nordenskiöld
" Nordmark, I	(70)	1.6986_y	1.7057_y	1.7271_y	0.0285	60° 28′	Wülfing
Hedenbergite, Tunaberg	(72)	1.7320_y	1.7366_y	1.7506_y	0.0186	59° 52′	Wülfing
Diallage, The Lizard		1.679	1.681	1.703	0.024	—	Lévy and Lacroix
Augite, Renfrew		1.6975_y	1.7039_y	1.7227_y	0.0252	61° 12′	Wülfing
" Boreslau		—	1.70	—	—	61°	Tschermak
" Auvergne		1.712	1.717	1.733	0.021	—	Lévy and Lacroix
" "		1.706	1.712	1.728	0.022	—	Lévy and Lacroix
" Frascati		—	1.74	—	—	68°	Tschermak
Jadeite		—	1.654	—	0.029	70° approx.	Lévy and Lacroix; Des Cloizeaux
Ægirite, Langesund	(59)	—	1.753_y	—	—	63° 28′$_y$	Brögger
" "		1.7630_y	1.7990_y	1.8126_y	0.0496	62° 13′$_y$	Wülfing
" Kola	(60)	1.777	1.801	—	—	—	(White light) Ramsay
Ægirite-augite		1.680	1.687	1.709	0.029	—	Viola

	Dispersion of bisectrices.	Dispersion of optic axes.	
Jadeite	—	$\rho > v$	Des Cloizeaux
Hedenbergite, Tunaberg	$X_{II} \wedge c > X_{II} \wedge c = 6'$	$li > tl = 16'$	Wülfing
Diopside, Nordmark, V	" " $= 13'$	" $= 18'$	"
" " IV	" " $= 11'$	" $= 28'$	"
" " V	" " $= 9'$	" $= 22'$	"
" Ala	" " $= 10'$	" $= 30'$	"
Ægirite, Langesund	$X_{II} \wedge c < X_{II} \wedge c = 1° 28'$	eosine $> tl = 51'$	"

Fig. 21 shows the position of the bisectrices and optic axes in the plane (010) for diopside, Ala, with an exaggerated statement of the dispersion. Fig. 22 shows the same thing for ægirite,

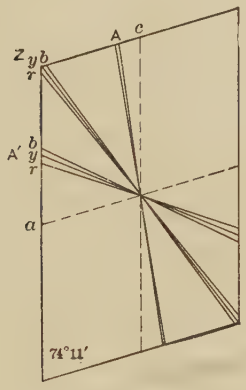

Fig. 21.

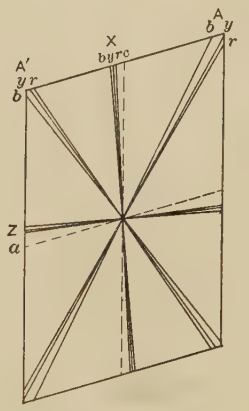

Fig. 22.

Langesund fiord. In diopside one optic axis emerges almost normal to the third pinacoid (001) and exhibits almost no dispersion. The other axis with more dispersion is nearly perpendicular to the first pinacoid (100). In diopsides and augites with greater inclination of the bisectrix Z to c one optic axis is more nearly perpendicular to (100) and in some cases the dispersion is more pronounced—titaniferous augites. In ægirite-augite the positions of the optic axes shift with the position of the bisectrices, as can be readily understood from a study of Fig. 20. In ægirite and acmite the dispersion of each of the optic axes and the bisectrices is nearly the same. The position of the optic axes with reference to the basal plane (100) is seen in Fig. 22.

From the foregoing data it is evident that the refraction of monoclinic pyroxene is high compared with that of feldspars, quartz, and Canada balsam, so that thin sections exhibit noticeable relief when surrounded by feldspars or quartz; outlines and cracks are pronounced and the surface appears shagreened in diaphragmed light. The double refraction is strong, yielding interference colors of the second order in ordinary thin sections. In ægirite the double refraction is high, the interference colors reaching the third order in most sections. Conical refraction is pronounced in sections at right angles to an optic axis; and in some varieties there is noticeable dispersion, as already noted. The double refraction of mono-

clinic pyroxenes is higher than that of orthorhombic pyroxenes, which serves to distinguish them in sections in certain positions.

Sections parallel to (010) exhibit the strongest double refraction ($\gamma - \alpha$) and yield the highest interference colors. In convergent light the symmetrical form of the interference figure shows the emergence of the optical normal Y, in the center of the field. In such sections it is possible to determine the angle of inclination of Z or X to the crystal axis c, which is parallel to the traces of the prismatic or pinacoidal cleavages.

In sections in the zone of (010) (100), that is, parallel to the c axis, the traces of the prismatic or pinacoidal cleavages are always parallel to one another and to the c axis. The extinction angles measured from the cleavage cracks range from the maximum in the plane (010) to 0 in (100).

In sections in the zone (100) (001), that is, parallel to the b axis, the traces of the prismatic cleavage intersect one another at various angles, which are 87° and 93° in sections perpendicular to c, and gradually change to 0° and 180° in the plane (100). In all of these sections the directions of vibration, positions of extinction, bisect the angles between the traces of the prismatic cleavage. They are parallel to the traces of the pinacoidal cleavage when present, these traces intersecting one another at 90° in all sections in this zone.

In sections in the zone (001) (010) parallel to the a axis the traces of the prismatic cleavage intersect one another in a manner similar to that in the zone (100)(001), except that one intersection varies from 87° in (001) to 180° in (010), while the other varies from 93° to 0°. In this series of sections the directions of extinction bisect the angles between the cleavage traces in only one case—when the section is parallel to (001). In all others the directions of extinction are unsymmetrical to the prismatic cleavage cracks.

The optical properties of pyroxenes twinned on (100) is readily understood. The twinned parts exhibit symmetrical extinction angles, that is, behave in exactly opposite manner, when they are cut by planes in the zone of either assumed twinning axis, axis of rotation c, or the normal to (100). The first is the zone (100)(010), the second is the zone whose planes are perpendicular to (100), the plane of symmetry for the twin. In all other positions the optical behavior of each of the twinned parts will be different.

Zonal Structure.—In some varieties of monoclinic pyroxene there is a pronounced zonal structure noticeable between crossed nicols, or visible in ordinary light. In the darker-colored varieties, titaniferous

augites, ægirite-augites, and ægirite-acmites, it appears as zones of different colors. In almost every case the lighter-colored zones are nearer the center of the crystal, the darker ones outside. In many cases where there is little or no recognizable difference in the color of zones in thin section there is a distinct difference in the double refraction seen between crossed nicols. The zones are sharply defined and differ in interference color and orientation, and to some extent in refractive index, which may be observed in diaphragmed light. The differences in some cases are progressive from the central part of the crystal toward the margin; in others there is an alternation from zone to zone without very great difference between the central and marignal zones. It is evident that the zones differ in chemical composition. In the sodic varieties the variation is uniformly from a less sodic central crystal to a more sodic and more ferric margin, a colorless augite having a margin of green or brown ægirite or acmite. In the diopside-augite series the central part of the crystal appears to be nearer the diopside end of the series, the outer part farther from it, that is, richer in Al_2O_3,Fe_2O_3.

Hour-glass Structure.—In pyroxenes exhibiting marked zonal structure and noticeable difference in composition it frequently happens that the optical orientation of the crystal is not zonally uniform, but there are slight optical differences in different areas of the section, which are regularly spaced in some cases and irregularly in others. The regularly spaced areas usually appear definitely oriented with respect to the crystal planes of the pyroxene, so that the crystal is divided into sectors which in longitudinal sections take a form suggesting that of an hour-glass (Fig. 23). Wedge-shaped areas extend from the ends of the prismatic section toward the center. In other positions of sections and in certain crystals the areas having different optical orientation are less regularly shaped. This phenomenon is especially noticeable in titaniferous augite, in certain nephelite- and leucite-bearing lavas, as tephrites and basanites. In these pyroxenes it is seen to accompany differences of color in the different parts of a crystal. The same is still more noticeable in certain ægirite-augite, ægirite, and acmite crystals from nephelite-syenites in Norway. In the case of acmite from Rundemyr it was pointed out by Brögger that the brown portions were added on to the pinacoidal faces and not to the prismatic; also on $(\bar{1}11)$ and $(\bar{1}01)$, Fig. 24. In other words, the chemical composition of the molecules added to the planes (100) and (010) differed from those added to the faces (110), and similarly for certain end faces.

Color, diopsides are colorless, pale green to dark green, also white or gray. In thin section they are colorless, sometimes pale greenish. Hedenbergite is black or greenish black, in thin section green. Augites are dark green to black, in thin section almost colorless to pale green; varieties richer in Fe_2O_3 are yellowish to pale brownish; those containing considerable titanium are often pale violet-brown, but may be green or colorless; ægirite-augite, ægirite, and acmite are black; in thin section they are strong green and greenish brown, and acmite is strong brown. Jadeite is colorless or white; in thin section colorless. The more strongly colored augites, besides ægirite and acmite, are pleochroic; the augites to a slight extent, ægirite and acmite to a marked degree. Ordinary augite is not perceptibly pleochroic. In some cases there is a slight difference in absorption in different directions.

	X	*Y*	*Z*	
Diallage	pale greenish	pale yellowish	pale greenish	*Ro.
Augite, basalt, Frascati	clove-brown	grass-green	olive-green	Ts.
Augite, tephrites	yellowish	reddish, brownish, greenish, or violet	yellowish	Ro.
Titaniferous augite	yellowish gray	reddish violet	yellowish red to violet	Ro.
Ægirite-augite	grass-green	sap-green	yellowish or brownish to greenish	Ro.
Ægirite, Langesund	deep olive-green to grass-green	olive green to grass-green	brown to brownish yellow, greenish tinge	Br.
Ægirite, Eker	deep grass-green	lighter grass-green	yellow-brown to yellow	Br.
" Låven	pure green to blue-green	olive-green	yellowish grass-green	Ro.
" Särna	blue-green	sap-green	yellow-green	Tö.
" Kola	pure green	yellow grass-green	brown-yellow	Ra.
" Azores	dark green	yellow-green	dirty yellow	Pa.
Acmite, Ditro	dark brown	brownish green	brownish green	Be.
Acmite, Rundemyr	light brownish with greenish tinge	greenish yellow with brownish tinge	Brownish yellow	Br.
Same, very thin section	greenish brown	yellow	greenish yellow	Ro.
Same, thicker section	dark brown	light brown	greenish yellow	Ro.

*Be. Becke; Br. Brögger; Pa, Pacheco; Ra. Ramsay; Ro. Rosenbusch; Tö. Törnebohm. Ts. Tschermak.

In ægirite and acmite, the absorption is $X > Y > Z$. As already said in connection with zonal structure, the color of monoclinic pyroxenes may be uniform for one crystal, or may vary zonally, or in sectors, or in an irregular manner. The darker-colored varieties are more commonly outside of the lighter-colored ones. To this there are exceptions in the titaniferous augites. The brown and green pleochroic ægirites and acmites are often mistaken for hornblendes. In most cases the monoclinic pyroxenes are much less pleochroic than the hornblendes.

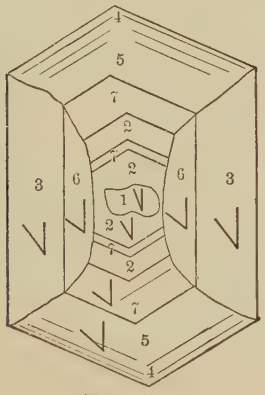

FIG. 23.

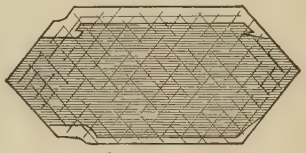

FIG. 24*a*.

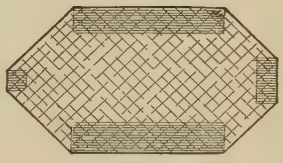

FIG. 24*b*.

Diallage sometimes has a bronze-like luster resembling bronzite, and due to the same kind of inclusions that occur in this mineral.

Inclusions.—The inclusions in monoclinic pyroxenes vary with the mode of occurrence of the pyroxene to a large extent. In many cases they are almost entirely absent. Gas inclusions occur quite generally in pyroxenes in coarser-grained rocks. In some instances the gas is carbon dioxide associated with the liquid form of CO_2. Liquid inclusions are not very common, but occur. Glass is enclosed to a variable extent in pyroxenes in lavas, often in great quantities. It sometimes is like the groundmass around the pyroxene and contains various microlites. Such inclusions may be holocrystalline.

Monoclinic pyroxenes frequently inclose crystals of other minerals associated with them in the rock, apatite, magnetite, etc. *Magnetite* in some cases is especially abundant, augite microlites being thickly sprinkled with it. Their frequent close association indicates an affinity for one another. *Ilmenite* rods, blades, plates, and grains occur in diallage and augite of certain gabbros and peridotites in the same manner as in enstatite and hypersthene. They are

arranged in several directions in planes parallel to (100), and sometimes parallel to a steep terminal plane. *Orthorhombic pyroxenes* are sometimes surrounded by monoclinic pyroxene in concentric parallel growth. Oftener the two are intergrown in laminæ parallel to (100) in the manner already described under orthorhombic pyroxene. The monoclinic variety is diallage or augite. *Hornblende* and *mica* are sometimes intergrown with pyroxene, but oftener they surround it as a later crystallization. *Lime-soda-feldspars*, especially labradorite, are frequently inclosed in augite in a poikilitic manner. In ophitic fabrics single crystals of augite act as a matrix for several feldspars, besides other minerals, as olivine, magnetite, etc. Feldspars are sometimes inclosed in an irregular manner in pyroxenes in other kinds of rocks. *Nephelite* and sometimes *sodalites* are inclosed by ægirite in a poikilitic manner. This is well shown in urtite from the Kola peninsula.

Modes of Occurrence.—Monoclinic pyroxenes are chiefly found in igneous rocks, especially in lavas. They are much less common in metamorphic rocks, though in certain varieties of these they are abundant or form the principal constituent. In igneous rocks they occur sparingly in the quartzose kinds, and become more and more abundant in less siliceous rocks richer in lime and ferromagnesian elements.

Diopside occurs in quite different kinds of igneous rocks, as already pointed out in connection with the chemical analyses: in certain granites, leucite-orthoclase-lavas, wyomingite and madupite, in some gabbros, basalts, pyroxenites, and picrites; its development in these magmas having been influenced by lack of available alumina. It is to be noted that it occurs both in lavas and in coarsely crystalline rocks.

Diallage, in part diopside, in part augite, is found in the coarser-grained rocks, such as gabbro, peridotite, pyroxenite. It does not occur in extrusive lavas.

Augite, varying in amounts of alumina and ferric oxide, is the most widely distributed pyroxene, occurring in igneous rocks of all degrees of crystallinity and granularity, and having a wide range of chemical composition. The varieties which are lighter colored in thin section occur in granites, syenites, diorites, and closely related rocks, except when the pyroxene approaches ægirite-augite, when it is stronger colored and green. The yellower and slightly pleochroic augites occur in the less siliceous rocks richer in iron, such as some gabbros, basalts, peridotites, and pyroxenites, certain nephel-

ite- or leucite-bearing rocks, and others. The violet-tinted, green or colorless, titanium-bearing augites occur in the same kinds of rocks as those last mentioned.

Ægirite-augite, *ægirite*, and *acmite* are found in the more alkalic rocks, both the coarse grained and the lavas, such as granites, syenites, nephelite-syenites, urtite, ijolite, and the porphyry and glassy forms of these and similar magmas. Consequently they do not occur in diorites, gabbros, peridotites, pyroxenites, or in their lava equivalents, the andesites, basalts, limburgites, and augitites.

Jadeite is found in phanerocrystalline and microcrystalline rocks whose field occurrence and geological character are in some doubt. The presence of albite and nephelite, however, in small quantities suggests an igneous origin.

As *secondary* crystallizations, that is, as products of alteration in igneous rocks, monoclinic pyroxenes are not common, as are the amphiboles. A light-colored diopside or augite has developed secondarily in a peridotite from Little Deer Isle, Me., according to Merrill.[1] It attaches itself as a secondary enlargement to violet-tinted augite, extending as sharp-pointed projections into adjacent serpentine. It also occurs isolated within the serpentine. Ægirite, in needle-like crystals, singly or in clusters accompanying zeolites, appears to be secondary in certain nephelite-syenites, tinguaite, and related rocks. Cross describes a secondary enlargement of colorless pyroxene by ægirite in a granite-like dike cutting gneiss in Colorado.[2]

In metamorphic rocks the monoclinic pyroxenes are diopside, hedenbergite, or augite, and possibly jadeite, but its mode of occurrence is in doubt. The two principal kinds of occurrence are the gneisses and crystalline schists and zones of contact metamorphism.

Since gneisses are so closely related to igneous rocks that they may in some cases be unaltered forms of igneous rock exhibiting original lamination, while in many cases they may be but slightly modified igneous rocks, it follows that the occurrence of pyroxenes in these rocks is nearly the same as in chemically similar igneous rocks, except that in general pyroxene is not so common in them, being frequently altered to amphibole. For this reason also it is seldom found in the more schistose rocks, though it sometimes forms massive lenticular layers interlaminated with the schists.

In contact zones, diopside, hedenbergite, and augite are often

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[1] Am. Jour. Sci., Vol. 35, 1888, p. 488.

[2] *Ibid.*, Vol. 39, 1890, p. 365.

developed, sometimes as minute components of dense hornstones, at others as large, well-formed crystals in calcite, together with other silicates, such as wollastonite, vesuvianite, garnet, etc.

Resemblances.—The monoclinic pyroxenes are most like the orthorhombic pyroxenes, which they resemble in cross-section and cleavage and in refraction, and to a large extent in color. The monoclinic varieties are distinguished by the inclined extinction in most longitudinal sections; those parallel to (100) having parallel extinction like the orthorhombic varieties. But sections in this plane (100), in diopside and augite, are at right angles to an optic axis, while in orthorhombic pyroxenes they are perpendicular to a bisectrix. There is a similar distinction in sections at right angles to the crystal axis *c*. Monoclinic pyroxenes having nearly the same colors as hypersthene are less pleochroic. The double refraction is stronger in the monoclinic forms, but sections nearly perpendicular to an optic axis exhibit low interference colors. The crystallographic position of such sections serves to distinguish the two forms as just stated.

Colorless diopside and augite closely resemble olivine in refraction and double refraction. But olivine has the higher double refraction in some sections, and may generally be distinguished from pyroxene by the absence of the characteristic cleavage, by its outward form or the habit of its crystals, and by its characteristic mode of alteration.

Monoclinic pyroxenes and amphiboles are much alike, having similar refraction, double refraction, and in some varieties similar colors. Their chief differences are in the angles of prismatic cleavage, that of amphibole being about 124° and 56°; and, in the habit of the crystals, cross-sections of pyroxene being commonly square or nearly octagonal, those of amphibole rhombic with two angles truncated symmetrically. Diopside and light-colored pyroxenes resemble in color tremolite and actinolite, which are usually in acicular prisms. Common hornblende is strongly colored, with pronounced pleochroism, which distinguishes it from diopside and augite in thin section. It resembles ægirite-augite, ægirite, and acmite, which are distinguished by pyroxene cleavage in cross-section, and by the difference in the bisectrices nearest the crystal axis *c*. In ægirite and acmite this is *X*, in hornblende it is *Z*. But it is *X* in arfvedsonite and riebeckite which occur in rocks, together with the sodic pyroxenes, and may be distinguished from them by their cleavage and colors, the sodic amphiboles having a blue or bluish tone in most cases.

Diopside and augite resemble epidote and zoisite in refraction

but epidote has stronger double refraction and zoisite very low double refraction. The characteristic greenish yellow of most epidote is also distinctive, together with the habit of the crystals when euhedral, and their optical orientation, the prisms being elongated parallel to the b axis.

Augite and diopside resemble melilite in refraction and color in some cases, but melilite is distinguished by its extremely low double refraction and blue interference color.

Laboratory Production.—Diopside and augite are readily produced in open crucibles from their molten constituents. They are common in many furnace slags. Monoclinic pyroxene crystallizes from the liquid obtained by melting hornblende. This is generally accompanied by the separation of magnetite. Fouqué and Michel Lévy obtained them in numerous experiments upon the crystallization of various mineral combinations in open crucibles. Augite has been produced by Daubrée by heating a glass tube in the presence of water-vapor.

SPODUMENE.

Composition: $LiAl(SiO_3)_2$.

Monoclinic: prismatic. $a:b:c = 1.1283:1:0.62345$, $\beta = 69° 32\frac{1}{2}'$.

Twinning: twinning and composition plane (100).

Cleavage: perfect, parallel to (110); parting parallel to (100), often prominent.

Fracture: uneven to subconchoidal. H. = 6.5–7. Sp. gr. = 3.17–3.19.

Optical Properties: biaxial. Plane of optic axes parallel to (010) optically (+), $Z \wedge c = 26°$ in obtuse angle β. Des Cloizeaux. $2V_r = 54°$ to 50°.

$$\alpha_y = 1.651, \quad \beta_y = 1.669, \quad \gamma_y = 1.677. \text{ Des Cloizeaux.}$$

Color: greenish to grayish white, yellowish green, emerald green (hiddenite), yellow, pale amethystine (kunzite). In thin sections colorless. *Luster:* vitreous, on cleavage surfaces somewhat pearly.

Chemical Composition.—Metasilicate of lithium and aluminium, $Li_2O \cdot Al_2O_3 \cdot 4SiO_2$, or SiO_2 64.5, Al_2O_3 27.4, Li_2O 8.1 = 100. Sometimes there is a little sodium, and in hiddenite there is a little chromium which may occasion the color.

Alteration.—Not acted on by ordinary acids. Spodumene alters to a variety of minerals. The changes in the spodumene of Branchville, Conn., have been specially studied. One mode of alteration is to a mixture of albite and eucryptite, in graphic intergrowth.

A subsequent stage in the alteration is a mixture of albite and muscovite, known as cymatolite. Microcline is also produced, and in some cases quartz and killinite, a cryptocrystalline aggregate having the composition of muscovite.

Crystal Forms and habit somewhat similar to those of diopside-augite, but the value of the axial angle, $\beta = 69° 31\frac{1}{2}'$, is slightly different from that in these minerals. Prisms parallel to the c axis, with pinacoids $a(100)$, $b(010)$, and the prism $m(100)$, besides other prism faces, and terminal planes less perfectly developed. Often flattened parallel to $a(100)$, Fig. 1. Crystals sometimes very large, 4 to 6 feet long and 1 foot broad. H. = 6.5–7. Sp. gr. = 3.170, hiddenite; 3.193, Branchville.

Twinning parallel to (100), as in other monoclinic pyroxenes.

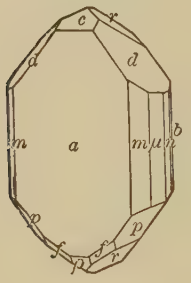


Fig. 1.

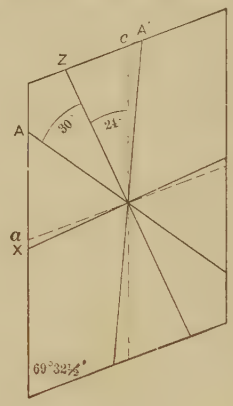


Fig. 2.

Cleavage. — Prismatic, with angles of 93° and 87°. Also pronounced parting parallel to the first pinacoid which separates the crystal into thin plates. This parting when combined with one of the prismatic planes of cleavage gives an obtuse angle suggesting that of tremolite, which may lead to confusion with this mineral.

Optical Properties.—Very similar to those of diopside. Biaxial with the plane of the optic axes in (010). Z is the acute bisectrix, optically (+), in obtuse angle β, Fig. 2.

Brazil,	$Z \wedge c = 23\frac{1}{2}°–24°$	Greim	
Alexander Co., N. C.	" $= 25°–25\frac{1}{2}°$	"	
	" $= 26°$	Des Cloizeaux	

	α	β	γ	$\gamma - \alpha$	$2V$	
Alexander Co., N. C.	1.651_y	1.669_y	1.677_y	0.026	—	Des Cloizeaux
Brazil,	1.660	1.666	1.676	0.016	$54°–60°_r$	Lévy and Lacroix

Color, greenish or grayish white, emerald green, yellow, amethystine, colorless in thin section. Thicker sections or crystals of green hiddenite are pleochroic.

Modes of Occurrence.—Spodumene occurs in granitic pegmatites with quartz, alkalic feldspars, muscovite, lepidolite, tourmaline, beryl, occasionally petalite, and with certain phosphate minerals. These rocks may be fine grained, but are oftener extremely coarse grained, the crystals being measured in feet, as at Branchville, Conn., and in the Black Hills.

LÅVENITE.

COMPOSITION: $Na(Mn,Ca,Fe)(ZrO,F)(SiO_3)_2$.

MONOCLINIC: prismatic. $a:b:c=1.0963:1:0.71509$, $\beta=69°\ 42\frac{1}{2}'$.

Twinning: Twinning plane and composition plane (100).

Cleavage: (100). H.=6. Sp. gr.=3.51–3.55.

OPTICAL PROPERTIES: biaxial. Plane of optic axes (010). $X \wedge c=19°\ 25'$ to $20°\ 18'$ in acute angle β. $2V=79°\ 46'$. $\beta=1.750$.

Color: colorless, yellow, also dark red-brown to black-brown. *Luster:* vitreous.

	I.	II.
Zircon	3.08	—
SiO_2	29.17	30.28
TiO_2	2.00	2.08
ZrO_2	28.90	30.00
$(NbTa)_2O_5$	4.13	4.29
Fe_2O_3	0.78	0.81
FeO	3.02	3.14
MnO	7.30	7.57
CaO	6.93	7.19
Na_2O	11.23	11.66
H_2O	0.65	0.67
F	3.82	3.97
	101.01	101.66
O for F	1.60	1.66
	99.41	100.00

Chemical Composition.—Låvenite is a silicate of sodium, calcium, manganese, and iron, which contains considerable zirconium, partly as a base, partly as acid, besides smaller amounts of fluorine, niobium, and titanium. A chemical analysis of material containing 3.08 per cent. of insoluble zircon is given in I., which reckoned without the zircon is II. Analyses of the lighter- and darker-colored varieties show that the percentage of MnO is greater in the darker-colored varieties, and that CaO and Na_2O are more abundant in the lighter colored.

Alteration.—Partly decomposed by hydrochloric acid. According to Brögger the light-colored låvenite appears to be a somewhat altered variety. The optical orientation and the double refraction are not uniform throughout a crystal, but

change noticeably from place to place. This variation is not observed in the dark-colored låvenites, which appear perfectly fresh.

Låvenite has undergone, in some instances, complete alteration to an aggregate of various minerals. This is not in the nature of weathering, but is probably an alteration brought about before the final solidification of the rock. Such pseudomorphs of låvenite, resembling those of mosandrite, consist of fluorite, colorless or deep violet-blue, which acts as a sort of matrix for the other constituents. The deep color is in streaks parallel to the *c* axis of the låvenite, suggesting that the alteration took place along the cleavage plane (100). Through the fluorite are scattered minute pyramidal crystals of zircon, anhedrons of magnetite, dark-brown anhedrons which are probably pyrochlore, besides abundant prisms of a yellow mineral with high refraction and strong double refraction, which Brögger considers to be a pyroxene of the ægirite series, poor in iron and probably containing zirconium. In places the aggregate is colored with hydrous oxide of iron.

Crystal Forms.—Låvenite crystallizes in monoclinic forms somewhat like those of ægirite or acmite, that is, in prisms parallel to the *c* axis, having *m*(110) well developed, *n*(210) subordinate, and *a*(100) usually present, *b*(010) being rare. Terminal planes are *e*(111) and *q*(101), Fig. 1, rarely (011). Tabular crystals parallel

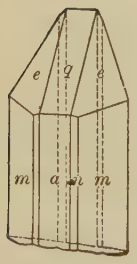


Fig. 1.

Fig. 2.

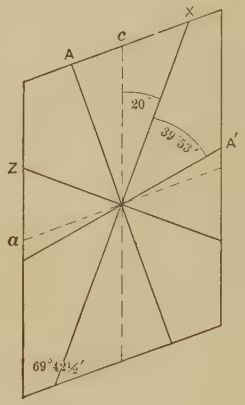


Fig. 3.

to *a*(100) are rare, Fig. 2. Euhedral crystals are the commoner forms, but rounded anhedral forms also occur.

Twinned crystals are frequent, there being several twinned

lamellæ in some cases. The twinning plane is (100), that of most common occurrence in pyroxenes.

Cleavage parallel to (100) is rather perfect. Fracture cracks are generally very numerous, the mineral being rather brittle.

Optical Properties.—Plane of the optic axes (010). The acute bisectrix X lies in the acute angle β of the crystal, the angle of inclination varying with the chemical composition and color (Fig. 3). Light-colored $X \wedge c = 19° 25'$; dark-colored $X \wedge c = 20° 18'$; dark-colored $2V = 79° 46'$; dark-colored $\beta_y = 1.750$ Brögger; $\gamma - \alpha = 0.03$ Lévy and Lacroix.

Låvenite is optically (−), but the large size of the optic angle makes it possible that some varieties may be optically (+); dispersion of the optic axes weak. The double refraction is slightly higher than that of diopside.

Color, colorless to yellow, also dark reddish brown to blackish brown. In thin sections colorless to pale yellow, with weak pleochroism. The darker-colored varieties are strongly pleochroic. X light wine-yellow, Y light yellowish green, Z deep orange-red to red-brown. $Z > Y > X$.

Modes of Occurrence.—Låvenite is a rare mineral found in a few localities in nephelite-syenite and pegmatite on the Islands of Låven and Arö in Langesund fjord, Norway. It has also been found in nephelite-syenite from Kassa, one of the islands of West Africa, and from Serra de Tingua, Brazil, and in tinguaites, acmite-trachytes, and phonolites, also in sanidinites from San Miguel, Azores.

Resemblances.—Låvenite resembles wöhlerite in color and in mode of occurrence, but differs from it in crystal habit, in slightly higher refraction and double refraction, and in optical orientation.

WÖHLERITE.

COMPOSITION: $12(Na_2,Ca)\cdot(Si,Zr)O_3\cdot RNb_2O_6$ with F.

MONOCLINIC: prismatic. $a:b:c=1.0549:1:0.7091$, $\beta=70°\ 45'$.

Twinning plane (100).

Cleavage parallel to (010) distinct. *Fracture:* conchoidal to splintery. H.=5.5–6. Sp. gr.=3.41–3.44.

OPTICAL PROPERTIES: plane of the optic axes perpendicular to (010). Inclination of acute bisectrix $X\wedge c=43°\ 15'$ in acute angle β. Z parallel to b. Dispersion small, $\rho<v$. Axial angle variable in a single crystal. $2V_r=71°\ 26'$ to $78°\ 18'$. $\beta_r=1.67$–1.72 Des Cloizeaux. Optically (−).

Color: light yellow, wine-, honey-, resin-yellow, brownish, grayish. *Luster:* vitreous to resinous. Pleochroism weak. Colorless to wine-yellow.

SiO_2	30.12
TiO_2	0.42
ZrO_2	16.11
Nb_2O_5	12.85
Ce_2O_3	0.66
Fe_2O_3	0.48
FeO	1.26
MnO	1.00
MgO	0.12
CaO	26.95
Na_2O	7.50
H_2O	0.74
F	2.98
	101.19
Less O for F	1.24
	99.95

Chemical Composition.—Wöhlerite is a zirconosilicate of calcium and sodium with small amounts of other bases and a notable amount of niobium and some fluorine. It is very similar in composition to låvenite, but contains less sodium and manganese and more calcium, less zirconium and titanium and more niobium. The percentage composition is given in the chemical analysis. Wöhlerite is readily attacked by hot concentrated hydrochloric acid.

Crystal Form.—Wöhlerite crystals are almost always tabular parallel to $a(100)$, Fig. 1. The tables are comparatively thick. Subordinate planes are $b(010)$ and several prisms $m(110)$, $n(210)$, $g(120)$, and $h(130)$. Also $c(001)$ and $k(\bar{1}01)$, frequently $d(101)$, besides $p(111)$, $s(\bar{1}11)$, and $o(011)$. Wöhlerite seldom appears in crystals of microscopic size, being usually megascopic. Twinning on (100) is common and there are often several twinned lamellæ, which are sometimes extremely thin. Cleavage parallel to (100) distinct, but incomplete, cleavage parallel to (110) doubtful. Fracture cracks abundant in all directions. H.=5.5–6. Sp. gr.=3.41–3.44.

Optical Properties.—The plane of the optic axes is perpendicular to (010); Z is parallel to the crystal axis b. The acute bisectrix X

lies in the acute angle β, and $X \wedge c = 43° 15'$ (Fig. 2). Wöhlerite is optically negative (−). There is noticeable horizontal dispersion and small axial dispersion, $\rho < v$. $2V = 78° 18'_{li}$, $78° 37'_{na}$, $78°49'_{tl}$ Brögger; $\alpha = 1.700$, $\beta = 1.716$, $\gamma = 1.726$, $\gamma - \alpha = 0.026$ Lévy and Lacroix.

The refraction and double refraction are about the same as in augite.

Color, usually bright honey-yellow to sulphur-yellow, seldom deep brownish yellow or colorless. In thin sections colorless to yellow, with distinct pleochroism, which is, however, not strong.

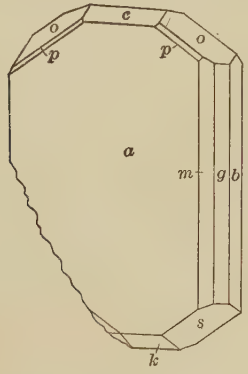


FIG. 1.

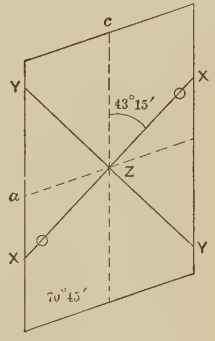


FIG. 2.

X colorless to light wine-yellow, Y colorless to light wine-yellow, Z deep wine-yellow. $Z > Y = X$.

Modes of Occurrence.—Wöhlerite is one of the commoner of the rare minerals found in the nephelite-syenite pegmatites of the Langesund region, occurring there in numerous localities.

Resemblances.—Wöhlerite is like hiortdahlite in color and pleochroism, and in refraction and double refraction, but is distinguished by its monoclinic character, which is recognized by the parallel extinction of polarized light in sections in the zone of the b axis; by the absence of twinning in sections parallel to $a(100)$ which are comparatively broad, and its presence in narrow sections inclined to this plane. Wöhlerite is also like låvenite in color, but has a different crystal habit, slightly lower refraction and double refraction, and different optical orientation.

ROSENBUSCHITE.

COMPOSITION: $Na_2Ca_3((Si,Zr,Ti)O_3)_4$.

MONOCLINIC: prismatic. $a:b:c = 1.1687:1:0.9776$, $\beta = 78° 13'$.

Cleavage: perfect parallel to (001), rather perfect parallel to (100) and ($\bar{2}01$). *Fracture:* uneven. H. = 5 – 6. Sp. gr. = 3.30 – 3.15.

OPTICAL PROPERTIES: plane of the optic axes and X at right angles to (010). X is in the acute angle β. $Z \wedge c = 12°$ to 14°. Index of refraction about 1.65, double refraction approximately 0.026.

Color: light orange-gray. *Luster:* vitreous.

SiO_2	31.36
TiO_2	6.85
ZrO_2	20.20
Ce_2O_3 (?)	0.33
Fe_2O_3	1.00
MnO	1.39
CaO	24.87
Na_2O	9.93
F	5.83
	101.66
Less O	2.45
	99.21

Chemical Composition.

$6CaSiO_3 \cdot 2Na_2ZrO_2F_2 \cdot (TiSiO_3 \cdot TiO_3)$ Brögger.

Rosenbuschite is a zirconosilicate of calcium and sodium, with titanium and fluorine. It is chemically somewhat similar to låvenite and wöhlerite, but is crystallographically more nearly related to pectolite and wollastonite. It may be considered as a zirconium-bearing pectolite. It is easily decomposed by hydrochloric acid.

Crystal Form.—Rosenbuschite occurs in prismatic crystals elongated in the direction of the b axis, Fig. 1, the planes forming the prism being $a(100)$, $c(001)$, and $s(\bar{2}01)$. Terminal planes are rare. In two cases they corresponded to $h(540)$. The crystals are usually slender, $\frac{1}{3}$ mm. thick by 1–2 cm. long, and occur in radiating groups. They may be microscopic in some cases.

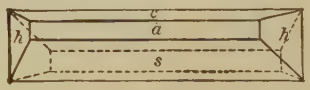


FIG. 1.

Cleavage is pinacoidal; perfect parallel to (001), less so parallel to (100), and imperfect parallel to ($\bar{2}01$). The basal cleavage appears as sharp cracks in thin section.

Optical Properties.—The plane of the optic axes is perpendicular to (010), with X parallel to b, and $Z \wedge c = 12°–14°$. But the large axial angle, which is probably about 90°, and the smallness of the sections studied, leaves the determination of the acute bisectrix and the optical character of the mineral in doubt. Brögger considers that Z is probably the acute bisectrix. Rosenbusch states that the refraction is about 1.65, judging from the relief in thin section, and that the double refraction is at most 0.026.

Color in crystals light orange-gray. In thin section colorless to pale yellowish with slight pleochroism but noticeable absorption, which is $Z > Y > X$.

Mode of Occurrence.—Rosenbuschite occurs in nephelite-syenite pegmatites of Norway, and in similar rocks from Brazil and North America.

Resemblances.—Rosenbuschite resembles pectolite and wollastonite in crystal habit and index of refraction, but the double refraction shown by longitudinal sections of rosenbuschite is lower than that of pectolite and higher than that of wollastonite. Moreover, the ray vibrating parallel to the long axis of the prism in rosenbuschite is always the fastest, X, while in pectolite it is the slowest, Z, and in wollastonite it is Y, which will be slower or faster than the ray vibrating at right angles to the long axis of the prism according to the position of the longitudinal section of the crystal.

Rosenbuschite also resembles sillimanite and carpholite in crystal habit, in refraction and double refraction, but in both of these minerals the ray which vibrates parallel to the long axis of the prismatic crystals of sillimanite, or nearly parallel to it in those of carpholite, is Z, the slowest, while in rosenbuschite it is the fastest, X.

PECTOLITE.

$HNaCa_2(SiO_3)_3$.

Chemical Composition.—Acid metasilicate of calcium and sodium. SiO_2 54.2, CaO 33.8, Na_2O 9.3, H_2O 2.7 = 100. Manganpectolite contains 4 per cent. of MnO. Decomposed by hydrochloric acid with separation of gelatinous silica.

Monoclinic: prismatic. $a:b:c = 1.1140:1:0.9864$, $\beta = 84° 40'$.

Crystal Form.—Pectolite occurs in thin prismatic crystals elongated parallel to the b axis. The faces forming the sides of the prism are $a(100)$ and $c(001)$, others quite subordinate; terminal planes $h(540)$, $\omega(140)$, etc., Fig. 1. Often in close aggregations of acicular crystals, usually radiating. Sometimes in massive, fine-grained aggregations. Twinning plane (100).

Cleavage.—Perfect parallel to (100) and (001), making angles of 84° 40′ and 95° 20′, resembling the prismatic cleavage in common pyroxene, but differently oriented. Fracture uneven. H. = 5. Sp. gr. = 2.68–2.78.

Optical Properties.—Axial plane perpendicular to plane of symmetry (010). Acute bisectrix Z parallel to b, X almost perpen-

dicular to (100). Optically (+). $2V=60°$, Fig. 2, $\frac{1}{3}(\alpha+\beta+\gamma)=1.61$, $\gamma-\alpha=0.038$ Lévy and Lacroix. In manganpectolite from Magnet Cove, Ark. $2E_y=15°$ approximately. Dispersion of optic axes nearly as strong as in titanite, $\rho>v$ J. F. Williams. Color whitish or grayish. In thin section colorless. Luster subvitreous to silky.

Mode of Occurrence.—Pectolite occurs in cavities or veins in basic igneous rocks, and to some extent in metamorphic rocks. Manganpectolite occurs in nephelite-syenite at Magnet Cove, Ark.

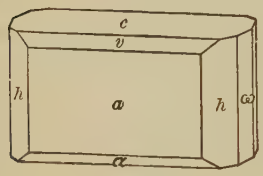


FIG. 1.

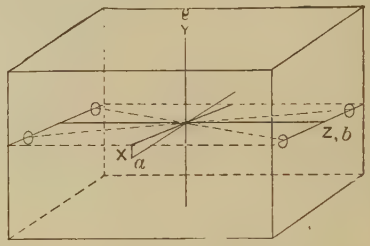


FIG. 2.

Resemblances.—Pectolite is like wollastonite, rosenbuschite, sillimanite, and carpholite. For the distinguishing characters see rosenbuschite.

WOLLASTONITE.

COMPOSITION: $CaSiO_3$.

MONOCLINIC: prismatic. $a:b:c=1.05312:1:0.96761$, $\beta=84°\ 30'$.

Twinning: plane (100).

Cleavage: (100) and (001) perfect, ($\bar{1}01$) less so.

Fracture: uneven. H. = 4.5–5. Sp. gr. = 2.8–2.9.

OPTICAL PROPERTIES: plane of optic axes (010). Optically (−). $X\wedge c=32°\ 12'$ in acute angle β. $2E_r=70°\ 40'$, $2E_v=68°\ 24'$ Des Cloizeaux. $\rho>v$. Inclined dispersion strong. Oravitza, $\alpha=1.621$, $\beta=1.633$, $\gamma=1.635$, $\gamma-\alpha=0.014$ Lévy and Lacroix.

Color: white, also grayish, yellowish, reddish, brownish. In thin section colorless. *Luster:* vitreous to pearly on cleavage surfaces.

Chemical Composition.—$CaO\cdot SiO_2=SiO_2$ 51.7, CaO 48.3 = 100. Decomposed with hydrochloric acid with separation of gelatinous silica.

Crystal Forms.—Tabular parallel $a(100)$ or $c(001)$, also prismatic parallel to the b axis (Figs. 1, 2, 3). Sometimes in fibers that may be parallel, or divergent. Besides the principal pinacoids $a(100)$ and $c(001)$ there may be other pinacoids parallel to the b axis as subordinate faces. A variety of terminal faces are sometimes developed, among them $h(540)$, $m(110)$, $x(120)$, and $z(320)$, but these are not well developed on crystals within rock masses.

Longitudinal sections are elongated rectangles, cross-sections are six- or eight-sided or rounded. The crystals may be anhedral and furnish irregularly shaped sections. Twinning parallel to (100) is common.

Cleavage is perfect parallel to (100) and (001), intersecting at angles of 84° 30′ and 95° 30′. There is sometimes less perfect cleav-

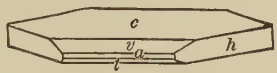


FIG 1.

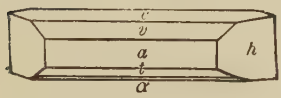


FIG. 2.

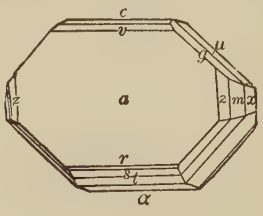


FIG. 3.

age parallel to $(\bar{1}01)$, which is the direction of the shorter diagonal of the traces of the more perfect cleavages. There is also in some instances a cleavage parallel to $(\bar{2}01)$. Fracture uneven. H.=4.5–5. Sp. gr.=2.8–2.9.

Optical Properties.—Plane of the optic axes parallel to (010), that is, across the length of the prism. The optic normal Y is parallel to b, the prismatic axis. The acute bisectrix $X \wedge c = 32° 12'$ in the acute angle β. Wollastonite from different localities differs as to the character of the acute bisectrix. In most cases the acute bisectrix is X, and the mineral is optically (−). But wollastonites from Montenarba, Sardinia, and from Aphroëssa, Santorin, are optically (+). $2V = 40°$.

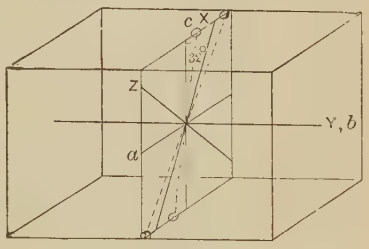


FIG. 4.

The dispersion of the optic axes is strong. $2E_r = 70° 40'$, $2E_v = 68° 24'$ Des Cloizeaux. $\rho > v$. Inclined dispersion of the bisectrices is strong, which may be seen in the color fringes on the hyperbolas of the optic axes; the hyperbola of one axis having blue fringes on both sides, that of the other axis having a red fringe on the concave (outer) side, and a blue fringe on the convex (inner) side.

Oravitza, $\alpha = 1.621$, $\beta = 1.633$, $\gamma = 1.635$, $\gamma - \alpha = 0.014$, Lévy and Lacroix
Pargas, $\alpha = 1.619$, $\beta = 1.632$, $\gamma = 1.632$, $\gamma - \alpha = 0.013$, Mallard

Color white, grayish, yellowish, reddish, brownish. In thin section colorless.

Inclusions.—There are no characteristic inclusions commonly occurring in wollastonite; it often contains fluid inclusions, calcite, garnet, diposide, and whatever minerals may be associated with it.

Mode of Occurrence.—Wollastonite oftenest occurs in metamorphosed rocks, especially crystalline limestone, also garnet- and epidote-rock. It occurs in schists containing calcic feldspars. It is formed by contact metamorphism of limestones, and is often found in limestone fragments inclosed in lavas of various kinds. It occurs sparingly in igneous rocks, as in nephelite-syenite of Alnö, which contains much calcite, and in some forms of ditroite from Ditro. Wollastonite is a primary constituent of nephelinite from Dönjo-Ngai, Masai-Land, Central Africa, where it is in parallel growth with augite and contains melanite and glass.

Resemblances.—Wollastonite is more or less similar to pectolite, colorless rosenbuschite, colorless epidote, zoisite, sillimanite, and carpholite. Its closest resemblances are to pectolite and rosenbuschite, having like crystal forms and index of refraction, but it differs from them in having lower double refraction, and in having the plane of the optic axes at right angles to the long axis of prismatic crystals, so that the ray Y vibrating in this direction is sometimes faster, sometimes slower than that vibrating at right angles to it. Whereas the same ray is always the fastest, X, in rosenbuschite, and always the slowest, Z, in pectolite. Wollastonite differs from epidote in having lower double refraction and from zoisite in having noticeably higher double refraction. In each of these minerals the axis of prismatic crystals, b, is the optic normal, Y. Wollastonite differs from sillimanite and carpholite in that the ray vibrating parallel or nearly parallel to the prismatic axis in each of these minerals is Z, and therefore the slowest in all positions.

Laboratory Production.—In most attempts to produce wollastonite by fusion of its constituents in an open crucible the mineral crystallizing has been a hexagonal or pseudohexagonal calcium metasilicate, sometimes in tabular crystals which are optically (+). Wollastonite has been produced by the fusion of silicates with borates of calcium and sodium (Hussak), also by the fusion of lime and silica with fluorides of calcium and sodium (Doelter). It has also been prepared from a glass obtained by rapid cooling of a fused mixture, having the composition of wollastonite, by heating to a temperature of 800°–1000° (Allen and White).*

* Am. Jour. Sci., vol. 21, 1906, pp. 89–108.

HIORTDAHLITE.

$4Ca(Si,Zr)O_3 \cdot Na_2ZrO_2F_2$.

Chemical Composition.—$4Ca(Si,Zr)O_3 \cdot Na_2ZrO_2F_2$, approximately.

SiO_2	31.60	MgO	0.10
TiO_2	1.50	CaO	32.53
Zr_2O_3	21.48	Na_2O	6.53
Fe_2O_3	0.34	H_2O	0.58
FeO	0.94	F	5.83
MnO	0.96		
			102.39
		less O	2.43
			99.96

Closely related to låvenite, wöhlerite, and rosenbuschite, which it also resembles in color.

Hiortdahlite is decomposed readily with hydrochloric acid with the separation of gelatinous silica. It alters to a leather-colored substance that has not been investigated.

Triclinic. $a:b:c = 0.99835:1:0.35123$; $\alpha = 89° 22\frac{1}{2}'$, $\beta = 90° 36\frac{5}{6}'$, $\gamma = 90° 5\frac{5}{6}'$.

Crystal Forms.—Thin blade-like crystals, two or three times as long as broad and often of extreme thinness. They are tabular parallel to $a(100)$ and elongated along the c axis (Figs. 1 and 2).

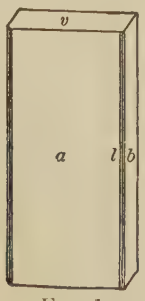


Fig. 1.

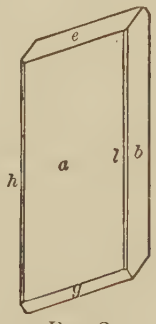


Fig. 2.

Often twinned in lamellæ parallel to $a(100)$, the twinning axis c. Cleavages not distinct, but rather straight cracks appear in sections cut parallel to (100), lying nearly symmetrical to the direction of the vertical axis.

Twinning axis c, composition plane (100).

Cleavage not distinct, very brittle. H. = 5+. Sp. gr. = 3.267.

Optical Properties.—Plane of the optic axes approximately parallel to $1\bar{1}1$. Acute bisectrix Z in upper left-hand front octant. Optically (+). Extinction angles read from c, on (100) = 25°, and on

$(010) = 15\frac{1}{2}°$. The angle between the optic axes is large, the index of refraction about 1.68–1.71, and the double refraction rather strong, ordinary sections yielding colors of the second or third order.

Color.—Light shades of straw-, sulphur-, honey-yellow, sometimes yellowish brown. Pleochroism weak, Z wine-yellow, Y bright yellow, X nearly colorless. Absorption $Z > Y > X$. Luster vitreous to greasy.

Mode of Occurrence.—Hiortdahlite has only been found in a small dike of nephelite-syenite on the Island of Middle Arö in the Langesund fjord.

HAINITE.

A silicate of sodium, calcium, possibly cerium, with titanium and zirconium. Magnesium and aluminium are absent. Decomposable in hydrochloric acid.

Triclinic; axial proportions undetermined. Jagged needles and spongy, broken plates. In the prism zone the planes are (100) pronounced; (010) small, and (hk0) very small. $(100) \wedge (010) = 78° 14'$, $(010) \wedge (hk0) = 31.5°$.

Twinning plane (100), contact twins.

Cleavage parallel to (010) rather distinct; parallel to (100) indistinct. Fracture uneven to conchoidal. H. = 5 approx. Sp. gr. = 3.184.

Optical Properties.—Optically positive (+); acute bisectrix Z nearly normal to (010). Extinction angle from the edge (100)(010) on (100) nearly 0°, on (010) 4°. In the section perpendicular to the prism zone it is 16.5° to the trace of (100). Extinction imperfect on account of strong dispersion of the bisectrices. $2E$ large. Dispersion strong, $\rho > v$. Refraction strong, about 1.7; double refraction about 0.012 at most.

Color.—Clear wine-yellow and pleochroic, X colorless, Y very light yellow, Z pale wine-yellow. Luster splendent to adamantine.

Occurrence.—Hainite occurs in phonolite at Hohen Hain near Mildenau, Bohemia, and in other phonolites in Bohemia.

Resemblance.—Hainite is somewhat like hiortdahlite in color and optical properties, but differs from it in optical orientation. In hainite the long axis of the crystals is always the direction of vibration of the slowest ray, Z, in hiortdahlite it is the direction of Y, and therefore in some positions that of the faster, in others that of the slower, ray.

AMPHIBOLE GROUP.

$RSiO_3$, with R = Ca, Mg, Fe chiefly, also Mn, Na_2,(K_2),H_2.

$\left\{\begin{matrix} RSiO_3 \\ {}^{II}_{R}{}^{III}_{R_2}SiO_6 \end{matrix}\right\}$ with $\overset{III}{R}$ = Al, Fe chiefly.

$\overset{I}{R}\overset{III}{R}(SiO_3)_2$, with $\overset{I}{R}$ = Na, and $\overset{III}{R}$ = Al, Fe.

Orthorhombic, Monoclinic, and Triclinic Systems.—Members of the amphibole group while crystallizing in three different systems agree in general habit and in having a similar prismatic cleavage of 54° or 56° (126° or 124°). They are similar chemically, or vary in composition through an isomorphous series with quite different extremes. They have optical similarities and form an optical series. There is a striking parallelism between the amphibole and pyroxene series, with certain differences which will appear in detail under each variety described.

Orthorhombic amphibole is rare and is confined to metamorphic rocks. Triclinic amphibole is also rare and is found only in igneous rocks. Monoclinic forms are abundant. In contrast to the pyroxenes, which usually form short, thick prisms and anhedrons, amphiboles often occur as slender prisms, sometimes fibrous. The pyroxenes are generally richer in calcium, the amphiboles richer in magnesium and iron. Amphiboles often contain more aluminium and alkalies than the pyroxenes. While both minerals occur in igneous and metamorphic rocks, amphiboles are commoner in metamorphic rocks, pyroxenes in igneous rocks.

The following list contains the chief rock-making amphiboles and their simplified formulas.

Orthorhombic Amphiboles.

Anthophyllite, $(Mg,Fe)SiO_3$.

Gedrite, $(Mg,Fe)SiO_3$ with $(Mg,Fe)Al_2SiO_6$.

Monoclinic Amphiboles.

Tremolite, $CaMg_3(SiO_3)_4$.

Actinolite, $Ca(Mg,Fe)_3(SiO_3)_4$.

Nephrite, asbestus, smaragdite, etc.

Cummingtonite, $(Mg,Fe)SiO_3$.

Grünerite, $FeSiO_3$.

Hornblende, $Ca(Mg,Fe)_2(SiO_3)_3$,
with $Na_2Al_2(SiO_3)_4$ and $(Mg,Fe)(Al,Fe)_2SiO_6$.

Edenite, pargasite.

Glaucophane, $NaAl(SiO_3)_2 \cdot (Fe,Mg)SiO_3$.

Riebeckite, $2NaFe(SiO_3)_2 \cdot FeSiO_3$.
Crocidolite, $NaFe(SiO_3)_2 \cdot FeSiO_3$.
Arfvedsonite, $Na_8(Ca,Mg)_3(Fe,Mn)_{14}(Al,Fe)_2Si_{21}O_{45}$.
Barkevikite.

TRICLINIC AMPHIBOLE.

Ænigmatite, $Na_4Fe_9AlFe(Si,Ti)_{12}O_{38}$.
Cossyrite.

ORTHORHOMBIC AMPHIBOLES.

COMPOSITION: Anthophyllite, $(Mg,Fe)SiO_3$.
Gedrite, $(Mg,Fe)SiO_3$ with $(Mg,Fe)Al_2SiO_6$.

ORTHORHOMBIC: crystal forms incomplete. $a:b=0.51375:1$.

Cleavage: perfect parallel to (110), also (100) and (010) less distinct. H. =5.5–6. Sp. gr. =3.1–3.2.

OPTICAL PROPERTIES: plane of optic axes (010). In all cases $Z \parallel c$, $X \parallel a$, and $Y \parallel b$. Anthophyllite usually optically (+). In anthophyllite from Franklin, N. C., the acute bisectrix is Z for red, parallel to c, and X for yellow and green, parallel to a, so that the mineral is optically positive (+) for red and negative (−) for yellow and green. Gedrite is optically negative (−). Indices of refraction and optic angle vary with the chemical composition.

Anthophyllite, Franklin, N. C., $\alpha_y=1.6288$, $\beta_y=1.6301$, $\gamma_y=1.6404$, Penfield and $2V_r=90°\ 4'$, $2V_y=88°\ 46'$, $2V_y=87°\ 28'$ about X, "

Color: brownish gray, yellowish brown, clove-brown, brownish green, emerald-green, sometimes metalloidal. In thin sections colorless to yellowish, reddish brown or yellowish green; pleochroic. *Luster*: vitreous to pearly on cleavage plane.

Chemical Composition.—Metasilicate of magnesium and iron with variable amount of aluminium. The more aluminous varieties are gedrite. Iron varies considerably both in the non-aluminous and aluminous varieties. Hydrogen is to some extent basic. The following analyses show the range of chemical composition:

	I.	II.	III.	IV.	V.
SiO_2	57.98	56.16	51.74	51.80	46.18
Al_2O_3	0.63	2.65	8.55	12.40	21.78
Fe_2O_3	—	—	—	—	0.44
FeO	10.39	14.13	20.35	3.67	2.77
MgO	28.69	23.19	16.45	27.60	25.05
CaO	0.20	1.51	1.79	—	—
Na_2O	—	—	—	1.44	2.30
H_2O	1.67	2.38	—	3.00	1.37
Ign	0.12	—	—	—	—
MnO	0.31	0.91	0.41	—	—
	99.99	100.93	99.29	99.91	99.89

I. Anthophyllite, Franklin, N. C. II. Anthophyllite, Kongsberg, Norway. III. Gedrite Stansvik, Finland. IV. Gedrite, Bamle, Norway. V. Gedrite, Fiskernäs, Greenland.

Alteration.—Unacted on by ordinary acids. Anthophyllite and gedrite are usually fresh, but in some cases have changed to talc.

Crystal Forms.—Common form prismatic, also lamellar or fibrous. Crystal faces developed in prism zone, (110) and (100). Terminal faces rare and not yet determined. Cross-sections rhombic (110) with angle of 54° 23′, sometimes six-side with development of (100). Crystals are in some cases aggregates of parallel prisms. In other cases there are aggregations of prisms which are not parallel, as is common with actinolite.

Cleavage.—Perfect parallel to (110), intersecting at angles of 54° 23′ and 125° 37′; also parallel to (010), bisecting the obtuse angle 125° 37′; and in some cases parallel to (100), bisecting the acute angle 54° 23′. There is an irregular parting nearly parallel to (001) which appears in thin sections as not very well-defined cracks.

Optical Properties.—Plane of the optic axes (010). The orientation of the bisectrices is the same in all varieties of orthorhombic amphiboles. $X \parallel a$, $Y \parallel b$, $Z \parallel c$ (Fig. 1). But on account of the large angle between the optic axes, nearly 90°, and the variations in α, β, γ, in various occurrences the acute bisectrix may shift from Z to X. In most anthophyllites the acute bisectrix is Z. They are optically positive (+). But in one from Franklin, N. C., the optical character is (+) for red light and (−) for yellow and green. Gedrite is optically negative (−). In some gedrite the value of $2V$ varies considerably in different crystals from the same locality. In general it may be said that the value of the negative optic angle, $2V_x$, decreases with increase in alumina and decrease in iron.

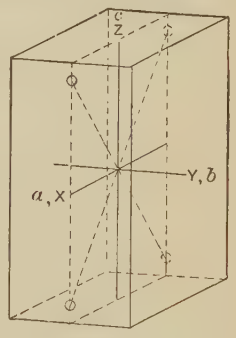


FIG. 1.

The dispersion of the optic axes is constant for all varieties of composition, $\rho > v$ about X, and $\rho < v$ about Z.

		r	v	g	
Anthophyllite, Franklin,	$2V_x$	90° 04′	88° 46′	87° 28′	Penfield
" Kongsberg,	$2V_x$	96° 12′	96° 06′	95° 45′	Des Cloizeaux
Gedrite, Fiskernäs,	$2V_x$	78° 33′	—	—	Ussing

In gedrite from Bräkke 2H.=47°−82°.

	α	β	γ	$\gamma-\alpha$	
Anthophyllite, Franklin,	1.6288_y	1.6301_y	1.6404_y	0.0116	Penfield
" Kongsberg,	1.633	1.642	1.657	0.024	Lévy and Lacroix
Gedrite, Fiskernäs,	1.623_r	1.6358_r	1.6439_r	0.0209	Ussing

Color.—Browns and greens; in thin sections colorless to yellowish, reddish brown or yellowish green. The stronger-colored varieties show distinct pleochroism.

Anthophyllite, Sörda Dalarne, Sweden, *X* yellow-white, *Y* yellow-green, *Z* bluish gray. Weibull.

" Lower Gondwana, India, *X* straw-yellow, *Y* claret-red, *Z* gamboge-yellow. Holland.

Inclusions.—Anthophyllite and gedrite sometimes inclose minute crystals of hematite, magnetite, picotite, and biotite, and occasionally contain inclusions like those commonly found in hypersthene. Orthorhombic and monoclinic amphiboles not infrequently occur intergrown as lamellæ parallel to (100). The two amphiboles have the *c* and *b* axes in each parallel. In all sections except those in the zone of (100)(001) they are readily distinguished by differences in optical orientation in alternate lamellæ.

Modes of Occurrence. — Orthorhombic amphibole occurs in gneisses and schists, sometimes as an essential constituent, sometimes in isolated aggregates usually radially grouped. It has been found in hornblende-mica-schist near Kongsberg, Norway; in actinolite-schist of the Lower Loire, and in numerous other localities. It occurs as an alteration-product with actinolite around olivine nodules in diorite-schist in Saxony. It accompanies bastite in serpentine derived from olivine, and surrounds altered olivine as a colorless zone in gabbro from the Lizard, Cornwall.

Resemblances.—Anthophyllite and gedrite are most like the monoclinic amphiboles, from which they are distinguished by their orthorhombic optical orientation and by their colors. All sections in the zone of the axis *c* extinguish light parallel to the traces of prismatic and pinacoidal cleavages, and the slowest ray, *Z*, vibrates parallel to *c*. The monoclinic amphibole approaching closest to the optical orientation is glaucophane with $Z \wedge c = 5°$, but this has blue colors. Riebeckite, with an extinction angle of only 5°, has *X* nearly parallel to *c*, and is blue. The monoclinic amphiboles with colors somewhat like those of orthorhombic amphiboles have noticeable extinction angles in sections nearly parallel to (010).

MONOCLINIC AMPHIBOLES.

Tremolite, $CaMg_3(SiO_3)_4$.
Actinolite, $Ca(Mg,Fe)_3(SiO_3)_4$.
Nephrite, asbestus, smaragdite, etc.
Cummingtonite, $(Mg,Fe)SiO_3$.
Grünerite, $FeSiO_3$.
Hornblende, $Ca(Mg,Fe)_2(SiO_3)_3$,
with $Na_2Al_2(SiO_3)_4$ and $(Mg,Fe)(Al,Fe)_2SiO_6$.
Edenite, pargasite.
Glaucophane, $NaAl(SiO_3)_2 \cdot (Fe,Mg)SiO_3$.
Riebeckite, $2NaFe(SiO_3)_2 \cdot FeSiO_3$.
Crocidolite, $NaFe(SiO_3)_2 \cdot FeSiO_3$.
Arfvedsonite, $Na_8(Ca,Mg)_3(Fe,Mn)_{14}(Al,Fe)_2Si_{21}O_{45}$.
Barkevikite.

Monoclinic: prismatic. $a:b:c = 0.5511:1:0.2938$, $\beta = 73° 58\frac{1}{4}'$; for arfvedsonite, $a:b:c = 0.55687:1:0.29781$, $\beta = 73° 2\frac{1}{4}'$. This is the orientation which corresponds to the parallel growth of pyroxene and amphibole. *Twinning* plane (100) common; rarely (001) lamellar.

Cleavage: (110) highly perfect, (100) and (010) sometimes distinct. Parting, due to twinning, sometimes observed parallel to (001) and (100). *Fracture:* subconchoidal. H. = 5–6. Sp. gr. = 2.9–3.4, according to composition.

Optical Properties: plane of the optic axes parallel to (010). Inclination of the bisectrices varies with the chemical composition.

	α_γ	β_γ	γ_γ	$\gamma - \alpha$	$2V_\gamma$	$Z \wedge c$
Tremolite	1.6065	1.6233	1.6340	0.0275	81° 22′	15°–18°
Actinolite	1.6116	1.6270	1.6387	0.0271	81° 27′	15°–18°
Pargasite	1.613	1.620	1.632	0.0190	58°–60°	18°–27°
Hornblende	1.630	1.642	1.653	0.0230	−84°	11°–20°
"	1.6398	1.6431	1.6561	0.0163	+53° 50′	—
Glaucophane	1.6212	1.6381	1.6390	0.0178	—	3°–11°
Gastaldite	1.6396	1.6563	—	—	−43° 58′	−6°
Basaltic hornblende	1.680	1.725	1.752	0.0720	−80°	0°–10°
Barkevikite	1.687	1.707	1.708	0.0210	—	0°–14°
Grünerite	—	1.73	—	0.056	—	11°–15°

Color: colorless, white through various shades of green to black, also brown, rarely yellow, pink, rose-red. In thin section colorless, green, greenish brown, brown, red, blue, bluish green, the darker-colored varieties strongly pleochroic in some sections. *Luster:* vitreous to pearly on cleavage faces.

Chemical Composition.—The monoclinic amphiboles are members of an isomorphous series of mixed salts whose chemical con-

stitution is not clearly understood. The various minerals of this series grade into one another, some having comparatively simple composition, others highly complex. They are metasilicates of magnesium, iron, calcium, chiefly, with basic hydrogen, and fluorine, and in some varieties aluminium, ferric iron, sodium, and a little potassium. There may also be manganese and in some varieties a notable amount of titanium. The variations in composition are shown in the accompanying table of analyses.

According to Tschermak's theory these elements may exist in the following possible molecular combinations: $CaMg_3(SiO_3)_4$, $Ca(Mg,Fe)_3(SiO_3)_4$, $(Fe,Mg)SiO_3$, $(Fe,Mn,Mg)SiO_3$, $FeSiO_3$, also $((K,Na)_2,Mg,Ca,Mn,Fe)SiO_3$, $NaAl(SiO_3)_2$, $NaFe(SiO_3)_2$, together with the hypothetical molecule $(Mg,Fe)(Al,Fe)_2(SiO_6)$.

Tremolite is almost wholly $CaMg_3(SiO_3)_4$. With increasing iron it grades into actinolite, $Ca(Mg,Fe)_3(SiO_3)_4$. Without calcium the monoclinic form is cummingtonite, $(Fe,Mg)SiO_3$. The almost pure iron amphibole is grünerite, $FeSiO_3$. The distinctly manganese variety is rare, danemorite, $(Fe,Mn,Mg)SiO_3$. The common amphiboles in igneous rocks, and in many metamorphic ones, contain aluminium and ferric iron, besides sodium and traces of potassium. Common hornblende consists of $(Ca,Mg,Fe,Na,K,H,Al,Fe)SiO_3$, in which calcium is about one quarter of all the bases, and is not one third of the magnesium and iron as usually stated in the text-books. Hydrogen and sodium sometimes form notable portions. The aluminium and ferric iron vary in amount in different varieties, apparently replacing the bases (Penfield). So-called basaltic hornblende is richer in ferric iron than common hornblende, and may contain considerable titanium. The more sodic varieties differ considerably in composition. Glaucophane is rich in aluminium and sodium. Riebeckite contains much ferric iron and sodium, like acmite, but also contains ferrous iron. Arfvedsonite and barkevikite are high in ferrous iron and sodium, with small amounts of other elements.

In the table of analyses the names of the igneous rocks are given from which the hornblendes and soda-amphiboles have crystallized, and it is seen that the less aluminous hornblendes develop in granites, quartz-monzonites, and quartz-diorites, that is, in the more quartzose feldspathic rocks. The alumina content increases in hornblendes crystallized from diorite and gabbro magmas; and is greatest in somewhat sodic amphiboles formed in certain alkalic magmas, as in sodalite-syenite of Square Butte, Montana, the camptonite of Dixville Notch, N. H., and the phonolite of Mayo, Cape Verde Islands.

ANALYSES OF AMPHIBOLES FROM METAMORPHOSED ROCKS.

	MINERAL. LOCALITY.	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	Ign.	TiO_2	MnO	F	Cr_2O_3	Total
1.	Theoretical, $CaMg_3(SiO_3)_4$	57.7	—	—	—	28.9	13.4	—	—	—	—	—	—	—	100.00
2.	Tremolite, Gouverneur, N. Y.	57.40	0.38	—	1.36	25.69	13.89	—	—	0.40	—	—	—	—	99.12
3.	Hexagonite, Edwards, N. Y.	58.54	0.30	—	0.44	25.16	10.43	0.98	—	0.63	—	2.39	0.41	—	99.28
4.	*Actinolite*, Greiner, Zillerthal	55.50	—	—	6.25	22.56	13.46	—	—	1.29	—	—	—	—	99.06
5.	*Cummingtonite*, Kongsberg	55.24	0.18	—	17.63	21.17	1.85	—	—	2.41	—	2.00	—	—	100.48
6.	" Baltimore, Md.	57.26	—	1.28	15.64	21.70	tr.	2.80	tr.	—	—	—	—	—	99.88
7.	" Cummington, Mass.	50.74	0.89	—	33.14	10 31	tr.	0.54	tr.	3.04	—	1.77	—	—	100.43
8.	" Räfvåla, Sweden	52.89	1.59	7.10	12.60	22.17	—	—	2.23	0.71	—	—	—	PbS 0.17	99.46
9	*Grünerite*, Collobrières	43.90	1.90	—	52.20	1.10	0.50	—	—	—	—	—	—	—	99.60
10	*Edenite*, Saualpe	49.33	12.72	1.72	4.63	17.44	9.91	2.25	0.63	0.29	—	—	0.21	—	99.13
11.	*Glaucophane*, Zermatt	57.81	12.03	2.17	5.78	13.07	2.20	7.33	—	—	—	—	—	—	100.39
12.	" Ile de Groix	56.65	12.31	3.01	4.58	12.29	2.40	7.93	1.05	—	—	—	—	—	100.02
13.	" Syra	55.64	15.11	3.08	6.85	7.80	2.40	9.34	—	—	—	0.56	—	—	100.78
14.	" Shikoku, Japan	56.71	15.14	9.78	4.31	4.33	4.80	4.83	0.23	—	—	—	—	—	100.15
15.	*Gastaldite*, St. Marcel	58.55	21.40	—	9.04	3.92	2.03	4.77	—	—	—	—	—	—	99.71
16	*Szechenyite*, Burma	55.02	4.53	1.04	3.28	20.36	8.00	6.71	0.52	0.51	—	—	—	—	100.97
17.	Crossite, Berkeley, Cal.	55.02	4.75	10.91	9.45	9.30	2.38	7.62	0.27	—	—	tr.	—	—	99.70
18.	Rhodusite, Sklipio, Island of Rhodusa	55.06	0.49	15.48	7.40	11.49	0.98	6.38	0.80	1.98	—	—	—	—	100.06
19.	Crocidolite, Cumberland, R. I.	51.03	—	17.88	21.19	0.09	—	6.41	—	2.64	—	—	—	—	99.94

ANALYSES OF AMPHIBOLES FROM IGNEOUS ROCKS.

	ROCK. LOCALITY.	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	Ign.	TiO_2	MnO	F	Cr_2O_3	Total
	Hornblende.														
20.	Durbachite, Durbach	54.89	1.50	5.06	7.46	16.01	12.08	0.37	0.38	2.72	—	—	—	—	100.47
21.	Mica-diorite, Böhmerwald	53.84	3.79	3.51	6.83	19.50	10.32	—	—	1.04	—	—	—	0.08	98.91
22.	Granite, Vosges	51.69	4.17	2.34	9.83	17.17	12.17	0.82	0.79	1.13	0.14	—	—	—	100.25
23.	Granitic syenite, Donegal, Ireland	47.25	5.65	19.11	0.94	11.26	11.76	0.98	1.04	—	—	1.70	—	—	99.69
24.	Monzonite, Monzoni	49.25	5.83	—	16.97	13.13	13.03	—	—	—	—	—	—	—	98.21
25.	Gabbro, Baste, Harz	52.13	6.18	1.14	9.06	17.30	14.32	—	—	0.73	—	0.14	—	—	101.00
26.	Quartz-monzonite, Butte, Mont.	45.73	6.77	4.94	10.39	12.32	11.25	0.77	1.22	2.78	1.43	0.54	0.28	P_2O_5 0.35	98.77

ANALYSES OF AMPHIBOLES FROM IGNEOUS ROCKS. (*Continued.*)

Rock. Locality.	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	Ign.	TiO_2	MnO	F	Cr_2O_3	Total
Hornblende.														
27. Quartz-monzonite, Yosemite Valley, Cal.	47.49	7.07	4.88	10.69	13.06	11.92	0.75	0.49	1.86	1.21	0.51	0.06	NiO 0.02 V_2O_3 0.04	100.05
28. Quartz-diorite, California	50.08	7.97	2.69	6.71	16.31	11.21	1.22	0.46	1.40	0.76	0.49	—	Cr_2O_3 0.16	100.46
29. Syenite, Biella	46.22	8.12	9.33	15.18	5.20	10.08	2.46	1.23	1.36	1.08	—	—	P_2O_5	100.26
30. Dacite, Grenatilla	45.76	8.80	5.32	11.23	14.08	10.62	1.39	0.26	0.85	1.43	0.57	—	—	100.31
30a. Tuff, Monte Rosso, Linosa	40.85	9.89	8.82	3.99	12.47	12.16	2.01	0.63	0.19	8.47	0.12	0.28	NiO 0.10	99.98
31. Hornblende-gabbro, Beaver Creek, Cal.	46.08	10.52	2.81	8.30	14.40	12.64	1.62	0.34	1.97	0.77	0.15	V_2O_5 0.04	0.18	99.99
32. Heumite, Heum, Norway	40.10	10.88	7.81	9.66	9.74	12.60	3.18	1.60	0.00	4.35	0.15	F 0.31	P_2O_5 0.63	101.01
33. Beerbachite, Koswinsky Kamen, Urals	40.52	10.99	9.64	9.83	11.82	12.33	2.38	0.68	0.50	1.71	tr.	—	0.43	100.44
34. Diorite, Ries	49.16	11.28	0.20	14.48	12.01	10.57	0.58	1.12	0.98	0.18	0.14	—	0.09	100.79
35. " Fetlar, Scotland	41.63	11.63	1.85	8.95	18.51	9.25	1.22	0.63	5.40	—	0.31	—	—	99.38
36. " Faymont, Vosges	41.99	11.66	—	22.22	12.59	9.55	1.02	—	1.47	—	—	—	—	100.50
37. " Schwarzenberg, Vosges	43.03	13.31	9.86	8.21	10.64	10.16	2.00	0.81	2.15	—	—	—	—	100.17
38. Hornblende-diabase, Gräveneck, Weilberg	41.35	13.48	5.14	10.33	11.44	10.93	2.10	0.62	0.48	4.97	—	—	—	100.84
39. Basalt tuff, Hohenberg, Giessen	40.14	14.30	6.27	7.07	11.62	12.00	2.22	1.35	—	4.26	0.21	—	—	99.44
40. Basalt, Czernosin, Bohemia	40.65	14.31	5.81	7.18	14.06	12.55	1.64	1.54	0.26	0.80	—	—	—	98.80
41. Hornblende-andesite, Hartlingen	40.15	14.34	7.80	4.53	13.14	11.75	2.31	1.14	—	5.21	—	—	—	100.37
42. Basalt, Jan Mayen	39.17	14.37	12.42	5.86	10.52	11.18	2.48	2.01	0.39	—	1.51	—	—	99.91
43. Basalt tuff, Okenberg, Vogelsberges	40.66	14.89	10.84	0.57	12.38	12.80	1.59	1.77	—	4.99	—	—	—	100.49
44. Hornblende-gabbro, Ivrea	39.58	14.91	4.01	10.67	13.06	11.76	2.87	0.62	2.79	tr.	tr.	—	—	100.27
45. Andesite, { Stenzelberg / Siebengebirge }	39.62	14.92	10.28	7.67	11.32	12.65	1.12	2.18	0.48	0.19	0.24	—	—	100.67
46. ——, Laacher See	39.05	15.45	6.39	7.03	11.28	13.75	1.34	0.94	—	4.68	0.31	—	—	100.22
47. Sodalite-syenite, Square Butte, Mont.	38.41	16.39	3.75	21.75	2.54	10.52	2.95	1.95	0.24	1.26	0.15	—	—	99.91
48. Camptonite, Dixville Notch, N. H.	40.79	17.36	3.83	15.04	6.97	10.83	4.17		0.71	—	0.30	—	—	100.00

ANALYSES OF AMPHIBOLES FROM IGNEOUS ROCKS. (*Continued.*)

ROCK. LOCALITY.	SiO	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	Ign.	TiO_2	MnO	F	P_2O_5	Total
Hudsonite.														
49. Quartz dike, Cornwall, N. Y.	36.86	12.10	7.41	23.35	1.90	10.59	3.20	1.20	1.30	1.04	0.77	—	—	99.72
Hastingstite.														
50. Nephelite-syenite, Dunganon, Ont.	34.18	11.52	12.62	21.98	1.35	9.87	3.29	2.29	0.35	1.53	0.63	—	—	99.61
Barkevikite.														
51. Nephelite-syenite, Barkevik	42.46	*11.45	6.18	19.93	1.11	10.24	6.08	1.44	—	*In SiO_2	0.75	—	—	99.64
52. Syenite, Brevik	42.27	6.31	6.62	21.72	3.62	9.68	3.14	2.65	0.48	1.01	1.13	—	—	98.63
Katoforite.														
53. Sanidinite, San Miguel. Azores	45.53	4.10	9.35	23.72	2.46	4.89	6.07	0.88	—	2.96	—	—	—	99.96
54. Comendite, San Pietro, Sardinia	49.10	5.50	4.20	27.70	0.17	0.13	10.50	1.60	—	—	0.50	—	—	99.40
Arfvedsonite.														
55. Nephelite-syenite, Kangerdluarsuk, Greenland	43.85	4.45	3.80	3.43	0.81	4.65	8.15	1.06	0.15	—	0.45	—	—	100.80
56. " " "	47.08	1.44	1.70	5.65	—	2.32	7.14	2.88	2.08	—	—	—	—	100.29
Riebeckite.														
57. Granite, Quincy, Mass.	49.65	1.34	17.66	19.55	—	3.16	7.61	—	1.67	—	—	—	—	100.64
58. Granite and syenite, Socotra	50.01	—	28.30	9.87	0.34	1.32	8.79	0.72	—	—	0.63	—	—	99.98

Hornblende crystallized from gabbro magmas varies in content of Al_2O_3 and Fe_2O_3, as in the analyses 25, 31, 44, according to the chemical composition of the magma, the more siliceous, less aluminous, varieties developing in the more siliceous gabbro magma.

Of the distinctly sodic amphiboles, arfvedsonite, barkevikite, and hastingsite occur in nephelite-syenite and syenite, while riebeckite, the variety richest in ferric iron, occurs in certain granites and syenites.

Alteration.—Monoclinic amphiboles of various kinds are undecomposed, or only slightly affected by hydrochloric acid. Their behavior toward ordinary processes of decomposition differs with their chemical composition. The chemically simpler varieties, like tremolite and actinolite, are more stable than the more complex hornblendes. In fact, the former frequently result from the breaking down of the more complex amphiboles.

Tremolite, when decomposed, alters in some cases to talc, in minute flakes or scales. *Actinolite*, which is rarely observed in a decomposed condition, changes to an aggregate which is probably serpentine associated with calcite. *Grünerite* alters into oxides and carbonates of iron, with quartz. *Common hornblende* and *basaltic hornblende* in some instances alter by the loss of color and subsequent passage into pale or colorless amphibole, resembling actinolite and tremolite; often becoming recrystallized as acicular or fibrous aggregates (*strahlstein*). In other and more frequent cases they alter to chlorite, usually accompanied by epidote, calcite, and quartz. Eventually they may change to carbonates, iron oxides, and quartz. Titanite sometimes results from the alteration of hornblendes containing considerable titanium. The *sodic amphiboles*, rich in iron and low in aluminium, arfvedsonite, barkevikite, and riebeckite, change upon decomposition to iron oxides and carbonates, with lievrite and little or no chlorite. *Glaucophane* in one instance described by Colomba has been altered to chlorite together with albite, some epidote, and hematite. In general, it appears unaltered.

In many lava forms of igneous rocks, especially the less siliceous, basaltic varieties, the hornblendes have undergone a more or less complete alteration to other minerals. However, the transformation is not a decomposition of the hornblende due to weathering or secondary processes subsequent to the solidification of the rock, but a recrystallization of the hornblende material while the surrounding rock magma was still molten. The complex hornblende molecule has passed into an unstable condition, and its constituents have been

recrystallized as other minerals. Within the space formerly occupied by hornblende, as shown by its outline, there may exist, as a zone surrounding unaltered hornblende, magnetite and pyroxene in an aggregate of minute crystals or anhedrons. When the parts are extremely minute, the mass appears black and opaque in thin section. When they are larger their character may be recognized. The pyroxene is both monoclinic and orthorhombic in some cases. In others there is, in addition, more or less lime-soda-feldspar. All of these minerals may be crystallized directly from the constituents of the hornblende. It is possible that in some instances there may have been an interchange of material between the hornblende and molten magma. It is to be noted in this connection that when hornblende is melted in an open crucible it crystallizes as a mixture of magnetite and pyroxene. A similar alteration of sodic amphibole to an aggregate of magnetite and diopside has been observed in the nephelite-syenite of Serra de Monchique. The barkevikite in the syenites of Norway is in some cases surrounded by a zone of ægirite and lepidomelane, in one instance, near Barkevik, accompanied by fluorite. It is a question to what extent such an aggregate is to be considered as derived from the amphibole, and to what extent it may be considered as an independent crystallization.

Crystal Forms.—The monoclinic amphiboles appear to be closely isomorphous, so far as their forms in the zone of the *c* axis indicate, but the more sodic varieties are not known in crystals with well-developed terminal faces. The varieties that are well developed and those that have been studied by etching belong to the prismatic class of the monoclinic system. The frequent parallel growth of amphiboles and pyroxenes with a constant orientation, as illustrated in Fig. 1, has led to a change in the choice of crystallographic axes of amphibole, which has caused some confusion in the literature on the subject, and differences of usage in text-books. The position here used is that employed by Tschermak in 1884 and by Dana (6th ed.), Rosenbusch (4th ed.), and others.

Monoclinic amphibole, $a:b:c = 0.55108:1:0.29376$, $\beta = 73° 58\frac{1}{4}'$.

The crystal habit is often that of slender prisms, though short, thick prisms and equidimensional crystals are common in many rocks. Lamellar crystals are rare. Fibrous aggregations, asbestus, are frequent in certain varieties, tremolite, actinolite, crocidolite.

The forms common to all varieties of monoclinic amphibole are $m(110)$, $b(010)$, less often $a(100)$, sometimes $e(130)$. The common terminal planes on tremolite, actinolite, and hornblende are $r(011)$

$p(\bar{1}01)$, sometimes $t(101)$, $o(121)$, and rarely $c(001)$. Some of the more frequent combinations of forms are shown in Figs. 2, 3, 4, 5, and 6. Crystals with the greater variety of faces occur in trem-

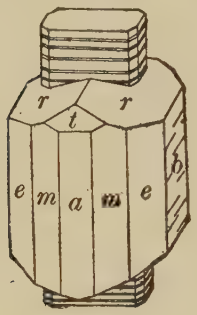


FIG. 1.

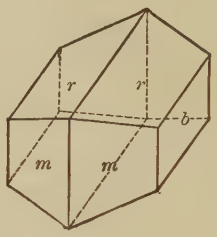


FIG. 2.

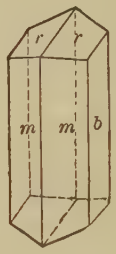


FIG. 3.

olite and actinolite. Those of hornblende are usually quite simple, having the unit prism (110) strongly developed, with the second pinacoid (010) subordinate, and less frequently the first pinacoid (100) quite small. When terminal faces are present they are usually $r(011)$ and $p(\bar{1}01)$. As the angle between the prism faces (110)

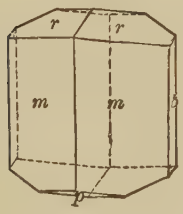


FIG. 4.

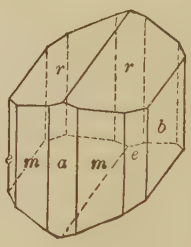


FIG. 5.

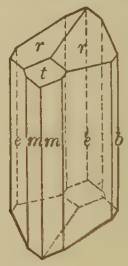


FIG. 6.

is 124° 11′, cross-sections are rhombic, usually with the acute angles truncated by (010), yielding 6-sided sections in contrast to the 8-sided cross-sections common to pyroxenes. Sections in other directions through the crystals are not characteristic.

Euhedral crystals are oftener developed in tremolite, actinolite, and hornblende when grown in metamorphosed limestones and on the sides of cavities, and in amphiboles in igneous rocks when they occur as phenocrysts in porphyries. Otherwise the crystals are subhedral, usually having definite faces in the prism zone parallel to the c axis, but lacking regular faces at the ends of the prisms. Anhedral crystals are very common, especially in the more evenly granular

rocks, both igneous and metamorphic, the best illustrations being the hornblendites and amphibolites.

Twinning.—The common case is that in which the twinning and composition plane is (100). In some instances there are several lamellæ in twinned position between the larger twinned parts. A second form of twinning is parallel to the basal pinacoid (001), and is usually polysynthetic. It is produced by pressure as in pyroxene, but is not often met with.

Cleavage parallel to (110) is generally highly developed, yielding in cross-sections straight cracks intersecting at approximately 124°, which is one of the most distinctive characteristics of amphibole. Cleavages parallel to (100) and (010) are sometimes distinct, but are rare. Parting parallel to twinned lamellæ is occasionally developed.

Fracture, subconchoidal to uneven, appears in thin section as irregular cracks, often nearly at right angles to the prismatic cleavage.

H. = 5–6. The specific gravity varies with the chemical composition, increasing with the content of iron in a general way from 2.930 in tremolite to 3.713 in grünerite.

Tremolite	Sp. gr. = 2.930–3.027	St. Gothard	
Actinolite	2.99	Felling	3.067 Greiner
Cummingtonite	3.068	Baltimore	3.15 Greenland
Glaucophane	2.991	Shikoku, Japan	
Crocidolite	3.2	Rhode Island	3.326 Dochfour
Pargasite, hornblende	3.112	Vesuvius	3.33 Jan Mayen
Barkevikite	3.428	Brevik	
Riebeckite	3.433	Colorado	
Arfvedsonite	3.454	Kangerdluarsuk	
Grünerite	3.713	Department du Var	

Optical Properties.—In the monoclinic amphiboles the plane of the optic axes lies in the plane of symmetry (010) with few exceptions. The bisectrix Z is situated in the obtuse angle β, between the crystal axes a and c. Its inclination to the axis c varies with the composition of the amphibole as shown in the diagrams; so do also the indices of refraction and the angle between the optic axes. Owing to the complex chemical composition of this series of minerals, there is no simple law correlating the composition and optical properties. The various groups of data are given in a series of tables. The orientations of the bisectrices X and Z in the plane (010) are stated in the diagrams (Figs. 7 and 8). Owing to the number of these that nearly coincide, they have been arranged in two groups, one containing the amphiboles chiefly formed in metamorphic rocks, together with those of secondary origin; the other group containing those

that are pyrogenetic. Some varieties, like common hornblende, occur in both groups. The data have been placed in the diagram corresponding to the source of the amphibole. In Fig. 7 it is seen that the bisectrix Z in nearly all amphiboles from metamorphic rocks lies within the obtuse angle β between the crystal axes c and a.

FIG. 7.—Amphiboles from Metamorphic Rocks.

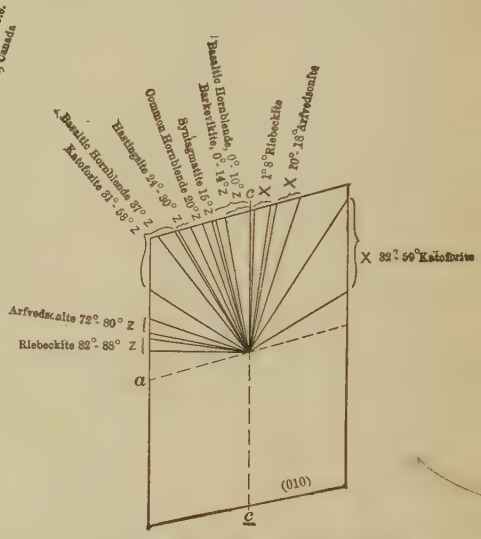


FIG. 8.—Amphiboles from Igneous Rocks.

In the different varieties the ranges of positions of Z coincide more or less completely, as indicated by the following data, which probably do not express the entire range in each case:

Glaucophane	$Z \wedge c$	3°–11°	in obtuse angle β
Gastaldite	"	6°	" "
Cummingtonite	"	6°–17°	" "
Common hornblende	"	10°–15°	" "
Grünerite	"	11°–15°	" "
Actinolite	"	15°–18°	" "
Tremolite	"	15°–17°	" "
Pargasite	"	18°–27°	" "
Crossite	$Y \wedge c$	20°–30°	" "
Blue hornblende (Rosita Hills)	$X \wedge c$	13°–15°	in acute angle β
Crocidolite	$X \wedge c$	18°–20°	in (?) angle β

Glaucophane and gastaldite have the smallest extinction angle measured from c. Cummingtonite, common hornblende, grünerite, actinolite, and tremolite have nearly the same range, though actinolite and tremolite do not appear to range so low as the first three

named. Pargasite grading into common hornblende reaches the highest limit of this series of amphiboles. The remaining varieties differ somewhat from the preceding in the position of the bisectrices or are not definitely known. In crossite the plane of the optic axes is normal to the plane of symmetry, according to Rosenbusch, with $Z \parallel b$ and the angle $Y \wedge c = 20°–30°$. According to Palache, $Y \parallel b$ and $X \wedge c = 13°$. In the blue hornblende described by Cross from Rosita Hills, Colo., the bisectrix X lies in the acute angle β and $X \wedge c = 13°–15°$. In crocidolite the bisectrix X is nearest c, with $X \wedge c = 18°–20°$ in that from Templeton, Canada, but it is not stated whether it lies in the acute or obtuse angle β.

In the amphiboles of pyrogenetic origin (Fig. 8) there is a somewhat more definite serial succession, though chemically different series of varieties coincide in their range of angular positions with respect to c. In nearly all these amphiboles the plane of the optic axes lies in (010), the only exception being the blue hornblende from Viezzena Thal, in which $Z \parallel b$. In all the other cases cited the bisectrix Z lies in the obtuse angle β, the angles $Z \wedge c$ ranging from 0° to almost 90°. The following is a list of extinction angles:

Basaltic hornblende	$Z \wedge c$	0°–10°	in obtuse angle β
Barkevikite	"	0°–12°, 14°	"
Kaersutite	"	10°	"
Soretite	"	17°	"
Common hornblende	"	19° 53′	"
Hastingsite	"	25°–30°	"
Katoforite	"	31°, 41°, 58°	"
Basaltic hornblende, Aranyer Berg	"	37°	"
Arfvedsonite	"	72°, 76°, 80°	"
Riebeckite	"	82°–88°.5	"

From this it is seen that basaltic hornblende and barkevikite have the same range of extinction angles measured from c to the bisectrix Z, the direction of vibration of the slowest ray. The same range of low angles is found in riebeckite and arfvedsonite, but in this case the bisectrix is X, the direction of vibration of the fastest ray. Common hornblende ranges from the more ferruginous varieties to hastingsite and katoforite, but only a single determination from a pyrogenetic " common " hornblende appears in the list. The high angle in the " basaltic " hornblende from Aranyer Berg is anomalous. Katoforite, as Brögger points out, appears to be intermediate in position between hornblende and arfvedsonite or riebeckite, corresponding to the place occupied by ægirite-augite in the pyroxene

INDICES OF REFRACTION OF MONOCLINIC AMPHIBOLES.

	α_y	β_y	γ_y	$\gamma-\alpha$	$2V_y$ $X(-)\cdot Z(+)$		$Z\wedge c$			
Tremolite, Skutterud	1.6065	1.6233	1.6340	0.0275	81° 22′	—	16°			Penfield
" Gouverneur	1.5987	1.6125	1.6239	0.0252	83° 52′	—	—			Zimanyi
" Felsö-Sebes	1.5996	1.6144	1.6266	0.0270	83° 32′	—	—			"
" St. Gothard	1.609	1.623	1.635	0.0260	80°–88°	—	15°	(white light)		Lévy & Lacroix
" "	—	1.622	—	—	87° 31′	—	15°		$\rho<v$	Des Cloizeaux
" Nordmark	—	1.618	—	—	84° 9′	—	17° 18′		$\rho<v$	Flink.
Actinolite, Fahlun	1.6004	1.6162	1.6284	0.0280	80° 38′	—	—	(light-green var.)		Zimanyi
" Zillerthal	1.6116	1.6270	1.6387	0.0271	81° 27′	—	—			"
" "	1.611	1.627	1.636	0.0250	80°	—	—	(white light)		Lévy & Lacroix
" St. Gothard	—	1.629	—	—	80° 4′	—	15°		$\rho<v$	Des Cloizeaux
Cummingtonite, Kongsberg	—	1.638_r	—	—	—	77° 52′	15°–17°	(yellowish-gray var.)	$\rho<v$	Haidinger
" Räfvåla	—	1.62–1.65	—	—	—	—	6°			Beck
Grünerite, Collobrières	—	1.73	—	0.0560	50°	—	11°–15° (β=average)			Lacroix
" Lake Superior region	—	—	—	0.0300	—	—	—			Lane
Pargasite, Pargas	1.613	1.620	1.632	0.0190	—	58°–60°	18°–21°			Lévy & Lacroix
" "	1.616	1.620	1.635	0.0190	—	52° 2′	—			Zimanyi
" Llanos de Juanar	—	1.64_r	—	—	—	59°	18°			Tschermak
	—	—	—	0.0230	—	—	—			Lévy
Glaucophane, Ile de Groix	1.6212	1.6381	1.6390	0.0178	—	—	—			Wallérant
" " "	—	—	—	0.0220	—	—	—			Lévy & Lacroix
" Zermatt	—	—	—	—	$\left\{\begin{matrix}2E \\ 85°\ 35'\end{matrix}\right\}$	—	4° 16′		$\rho<v$	Bodewig
" —	—	1.644	—	0.0216	42°	—	—			Lévy & Lacroix
Gastaldite, Aosta	1.6396	1.6563	—	0.0178	43° 58′	—	—			Bodewig
" "	—	—	—	0.0240	—	—	6°			Lévy & Lacroix

INDICES OF REFRACTION OF MONOCLINIC AMPHIBOLES. (*Continued.*)

		α_y	β_y	γ_y	$\gamma-\alpha$	$2V_y$	$Z\wedge c$		
Common hornblende,	Kragerö	1.629	1.642	1.653	0.0240	84°	—	—	Lévy & Lacroix
" "	Volpersdorf	—	1.642_r	—	—	—	85° 4′	19° 53′	Tschermak
" "	Arendal	—	—	—	—	—	—	17° 30′	"
" "	Kafveltorp	1.6398	1.6431	1.6561	0.0163	—	53° 50′	—	Zimanyi
Soretite, Koswinsky	Kamen	1.6628	1.6765	1.6856	0.0228	—	82° 30′	17°	Duparc & Pearce
		1.6590	1.6701	1.6801	0.0211	—	90°	17° 30′	
Basaltic hornblende,	Bohemia	1.680	1.725	1.752	0.0720	80°	—	—	Lévy & Lacroix
" "	"	—	—	—	—	—	—	1°–2°	Des Cloizeaux
" "	Czernosin	—	1.710	—	—	79° 24′	—	—	Haidinger
" "	"	—	—	—	—	—	—	1° 40′	Tschermak
" "	Aranyer Berg	—	—	—	—	—	$\left\{\begin{matrix}2E \\ 67° 37′\end{matrix}\right\}$	—	Franzenau
Kaersutite, Kaersut		—	—	—	—	—	—	10°	Ussing
Barkevikite, Langesund		1.687	1.707	1.708	0.0210	—	—	—	Lévy & Lacroix
" —		—	—	—	—	(−)	—	14°	Rosenbusch
Arfvedsonite, —		—	—	—	—	—	—	$\frac{X\wedge c}{10°–14°}$	—
" —		—	—	—	—	—	—	18°	Hackman
Riebeckite, Dahamis, Socotra		—	—	—	—	—	—	8°	Pelikan
" —		—	—	—	—	—	—	4°–5°	—
" Gloggnitz		<1.687	—	>1.687	0.0051_{bl}	—	—	1.5°–2°	$\rho<v$ Keyserling

series. This apparently regular gradation in the optical orientations of the pyrogenetic amphiboles does not correspond to an equally regular transition in their chemical compositions.

In the matter of indices of refraction and the angles between the optic axes there is considerable divergence among the various amphiboles studied, and much remains to be learned regarding the optical constants of the darker-colored varieties, and of those occurring mainly as small crystals in rocks. From the accompanying data it is seen that the lowest indices of refraction measured occur in tremolite, $\alpha = 1.5987$. In the series from tremolite to grünerite the refringence increases slightly in actinolite, somewhat more in cummingtonite, and is highest in grünerite, the variety rich in ferrous iron. The double refraction is nearly the same in tremolite and actinolite, 0.025 to 0.028, and is twice as great in grünerite from Collobrières, 0.056, but is only 0.030 in a variety from the Lake Superior region. In all of these amphiboles so far as studied, the dispersion of the optic axes is $\rho < v$ and weak. The angle between the optic axes $2V$ is large, and the acute bisectrix is X in all cases but that of cummingtonite, in which it is Z. Tremolite, actinolite, and grünerite are optically negative (−), while cummingtonite is positive (+).

Of the aluminous amphiboles, pargasite low in iron has nearly the same index of refraction as those of tremolite and actinolite. It is slightly higher in glaucophane, and still more so in gastaldite. The same is true for common hornblende, the varieties richer in iron having higher indices of refraction, the highest being found in "basaltic" hornblende and barkevikite, which have nearly as high refraction as grünerite. The double refraction in these aluminous amphiboles is slightly lower than in the tremolite-grünerite series, $\gamma - \alpha$ ranging from 0.0163 to 0.0240 with one exception, the basaltic hornblende from Bohemia, with $\gamma - \alpha = 0.0720$. In the variety of katoforite from San Miguel, Azores, the double refraction is very low; the axial dispersion is strong, but $\rho > v$. The values of $2V$ vary from 42° in some glaucophane, and about 60° in pargasite, to high angles in hornblendes. The acute bisectrix, however, differs in different varieties of these amphiboles, and also in different crystals of similar varieties. In pargasite the acute bisectrix is Z, which is optically positive (+). In glaucophane and gastaldite it is X, optically negative (−). In hornblende it is X in some cases and Z in others. The axial dispersion is $\rho < v$ and strong in glaucophane. The refractive indices of arfvedsonite and riebeckite have not been determined.

In riebeckite from Gloggnitz the double refraction is very low, $\gamma-\alpha=0.0051$ for blue, the axial dispersion is $\rho<v$, and the optical character positive (+).

The dispersion of the bisectrices in the plane (010) varies from a slight amount in tremolite, actinolite, and common hornblende to considerable in the basaltic hornblendes and the alkalic amphiboles, yielding inclined dispersion in most cases, since the plane of the optic axes lies in (010). In basaltic hornblendes the direction of dispersion is not the same for all cases observed; sometimes $Z_\rho \wedge c < Z_v \wedge c$, at others it is the reverse. In glaucophane $Z_\rho \wedge c > Z_v \wedge c$. In arfvedsonite and riebeckite $X_\rho \wedge c < X_v \wedge c$, the dispersion in riebeckite being somewhat less than that in arfvedsonite. In all three of these cases the dispersion is in the same direction because the angles $Z \wedge c$ and $X \wedge c$ are measured on opposite sides of the axis c.

From these data it is seen that the refraction of monoclinic amphiboles is high compared with that of feldspar, quartz, and Canada balsam, so that thin sections of amphibole in rocks containing feldspar, quartz, and nephelite exhibit noticeable relief with pronounced outlines, having dark cracks and a shagreened surface when mounted in balsam. The refraction is slightly lower than that of the pyroxenes with which they are oftenest associated; the double refraction is nearly the same in these two groups of minerals, but the interference colors of the second order in ordinary thin sections are not so noticeable in hornblendes and the darker-colored amphiboles as in pyroxenes, owing to the stronger absorption of parts of the light in these amphiboles. They are clearly recognizable in the light-colored sections of actinolite and tremolite.

Marked dispersion of the optic axes is observed on the hyperbola emerging nearly normal to (100) in certain hornblendes. In the alkalic amphiboles, with strong dispersion of the bisectrices in (010), sections parallel to this plane do not show complete extinction in any position between crossed nicols.

Sections parallel to (010) exhibit the strongest double refraction except in the few amphiboles in which the plane of the optic axes is normal to this plane.

The optical behavior of monoclinic amphiboles in sections situated in the zones (001) (010), (100) (001), and (001) (010) is similar to that described for monoclinic pyroxenes and need not be restated.

Color.—In thick plates and crystals tremolite is colorless to white and dark gray, pink to violet-tinted in hexagonite, which contains

a little manganese; greenish-tinted from ferrous iron as it grades into actinolite, which is bright green to grayish green. Cummingtonite and grünerite are grayish brown to brown. Pargasite and common hornblende are bright green to dark green, sometimes bluish green, often black. The lighter colors are usually found in pargasite, the darker ones in hornblende. Of the alkalic amphiboles glaucophane is blue to bluish black; crocidolite is lavender-blue or green; arfvedsonite, barkevikite, and riebeckite are black.

In thin sections the lighter-colored varieties are colorless or pale shades of the colors shown in megascopic crystals; the black varieties are strongly colored in greens, blues, browns, and reds. Most amphiboles exhibit pleochroism which is more pronounced in the darker-colored varieties and is quite varied in tints. In general it may be said that the colors in actinolite are yellows and greens; in grünerite, brown; in pargasite, greens, also yellowish, bluish, and pinkish; in common hornblende, greens, also yellowish and brownish to browns, which dominates in the basaltic hornblendes, which are olive-green, browns, and sometimes reds; in barkevikite and katoforite browns preponderate, being sometimes yellowish or reddish. In the sodic amphiboles blue tones are common. In arfvedsonite the colors are blue, greenish blue, lavender-blue, violet, greenish yellow, yellow to brownish in some cases. Similar colors occur in riebeckite, glaucophane, crocidolite, crossite, and other varieties The specific pleochroism noted in different amphiboles is given in the accompanying table.

Zonal structure produced by variations in the chemical composition of amphibole crystals is not very commonly met with. Zones of different colors or shades of color sometimes develop, but it usually appears as though the crystal is homogeneous in composition from center to margin. In some instances the central portion of a crystal of common hornblende is brown with the outer portion green. In other cases the outer portion is darker than the central. Zonal variation in the color and composition of the alkalic amphiboles has been noted, but it is not so common or so pronounced as in the pyroxenes. In such cases arfvedsonite surrounds barkevikite or katoforite.

Hour-glass structure is sometimes developed in the amphiboles richer in TiO_2, as is the case with the pyroxenes. There are variations in color in amphiboles that are not regularly distributed in the crystal, but occur in irregularly shaped patches. These are sometimes due to alteration of the original mineral. It frequently

	X	Y	Z	
Actinolite, Zillerthal	greenish yellow	yellowish green	emerald-green—in thick plates	Tschermak
" "	pale yellowish	pale yellowish	green—in thin plates	Lévy & Lacroix
Grünerite, Collobrières	colorless	colorless	light brown	"
Pargasite, Pargas	greenish yellow	emerald-green	greenish blue	Tschermak
" Llanos de Juanar	pale greenish	greenish	greenish pink	Lévy & Lacroix
Common hornblende, Krageroe	pale green	green	dark green	"
" " Volpersdorf	yellowish green	yellow	brown	Tschermak
Soretite, Koswinsky Kamen	pale greenish yellow	greenish	deep greenish	Duparc & Pearce
" " "	very pale yellowish	brownish	deep brownish	"
Carinthin, Saualp	yellowish green	yellowish brown	greenish brown	Tschermak
Common hornblende, Pressburg	yellowish green	brownish green	black-brown	"
Basaltic hornblende, Bohemia	pale brown	brown	dark brown	Lévy & Lacroix
" " Cernosin	honey-yellow	brownish red	black-brown	Tschermak
" " Aranyer Berg	olive-green	yellowish brown	greenish brown	Franzenau
" " Cabo Frio	light yellowish brown with greenish tint	dark gray-brown	grayish or greenish brown	Osann
" " Beverley	greenish yellow	olive-green	blue-green	Wright
Barkevikite, Norway	light brownish yellow	reddish brown	deep brown	Brögger
Kaersutite, Kaersut	light brown	dark reddish brown	darker reddish brown	Ussing
Katoforite, Lougenthal	light orange	brown-red	light reddish yellow	Brögger
" Grusletten	reddish yellow	brown-red	light greenish yellow	"
" Kaptainshöiden	light reddish gray	brownish red to greenish brown	light greenish blue	"
" Gilgil, E. Africa	yellowish pink	pink	pale reddish brown	Prior
" San Miguel, Azores	brown	dark brown to black	dark green-brown	Osann
Arfvedsonite, Greenland	greenish blue	blue to gray-blue	greenish gray to yellow	Rosenbusch
" "	very deep greenish blue	lavender-blue	pale greenish yellow	Ussing
" "	very dark bluish green	deep blue-green, with grayish tint	light brownish green	"
" "	deep Berlin blue	light grayish blue	light grayish green	"

PLEOCHROISM IN AMPHIBOLES. (*Continued.*)

	X	*Z*	*Z*	
Arfvedsonite, Apache Mts.	dark blue	gray-blue	light yellowish green	Osann
" " "	deep blue-green	deep blue-green	light yellowish gray	"
" Umptek	dark green	grayish violet	brownish gray to steel-gray	Hackman
" "	dark green	light yellowish brown	greenish brown	"
Hastingsite, Hastings Co., Ont.	yellowish green	deep blue-green	deep blue-green	[ton Adams & Harring-
Riebeckite, Socotra	deep blue	somewhat lighter	green	Rosenbusch
" Ailsa Craig	deep blue	deep blue	yellowish or greenish brown	Teall
" Corsica	indigo, almost black	blue	yellowish green	Le Verrier
" El Paso, Cal.	very dark blue	greenish blue	pale yellowish green	Lacroix
" Narsasik, Greenland	very deep indigo-blue	dark blue-gray	light yellowish green	Ussing
" Gloggnitz	deep dark blue	violet-blue to steel-blue	brownish, yellowish green	Keyserling
" Dönjo Buru, E. Africa	deep indigo-blue	deep blue to opaque	pale brownish yellow	Prior
" Alter Pedroso, Portugal	greenish blue	grayish blue	yellowish brown	de Souza-Brandão
Crocidolite, Orange River, Africa	green	violet	violet	—
" Templeton, Canada	greenish blue	violet-blue	light green	Lacroix
" Narsasik, Greenland	blue	gray-violet	nearly colorless	Ussing
Blue hornblende, Rosita Hills, Colo.	deep blue	purple to violet	pale yellow	Cross
Crossite, Berkeley, Cal.	colorless to greenish or grayish yellow	sky-blue to dark blue	gray-violet	—
Glaucophane, Zermatt	light greenish yellow	violet	ultramarine blue	Bodewig
" Val d'Aosta	yellow-green	violet	azure-blue	Strüver
" Isle Groix	greenish yellow	blue-violet	lavender-blue	Barrois
" Ocha	colorless (yellow-green)	reddish violet	azure-blue	Becke
" Shikoku	bluish-green	lavender-blue	bluish brown	Koto

happens that the hornblendes in andesites and other lavas are bright red in thin section; this is probably due to a change in the oxidation of the ferrous iron, produced by a dissociation of the water vapor in the rock, as it is quite local in some instances, and appears in other ferrous minerals, as mica and hypersthene, associated with the hornblende. Experiments by Belowsky and also by Schneider upon the effects of heating hornblende in the presence of air or superheated water vapor show a change of green colors to browns, owing to the further oxidizing of ferrous iron. Schneider also found a change in the values of $Z \wedge c$ from 2° or 8° to 0° in basaltic hornblende.

Inclusions.—The amphiboles are not especially characterized by any particular kind of inclusions. They may naturally inclose any mineral associated with them except younger pyrogenetic ones. Tremolite and actinolite are generally free from inclusions, with the exceptions just noted. Hornblende is often quite free from inclusions, but often incloses apatite, magnetite, and titanite in the igneous rocks, and sometimes rutile in the metamorphic ones. Gas or fluid inclusions are rare, as are also glass inclusions when in lavas.

Parallel growths of amphibole and pyroxene are frequent, the amphibole forming a zone about the pyroxene; hornblende surrounds augite, diopside, or hypersthene; the alkalic amphiboles inclose ægirite-augite or ægirite. In some instances the two minerals are irregularly intergrown. In either case they have the *c* axes and the *b* axes parallel. This is sometimes brought about by metamorphic or secondary processes, but is oftenest pyrogenetic, primary, crystallization. A frequent case of the secondary production of amphibole from pyroxene is that of uralite. Biotite is often inclosed in hornblende in the phanerocrystalline igneous rocks and lepidomelane is similarly associated with the alkalic amphiboles, as primary, pyrogenetic, crystals. The association of magnetite and pyroxene with hornblende as a pyrogenetic alteration has already been noticed. Hornblende sometimes acts as a matrix for all the other minerals associated with it, as in poikilitic hornblende in certain peridotites, when it incloses pyroxenes, olivine, sometimes feldspar, and other minerals.

Modes of Occurrence.—Monoclinic amphiboles occur abundantly in igneous and metamorphic rocks; certain varieties, however, are distinctly pyrogenetic, others wholly metamorphic or secondary, while some crystallize with like characters both from molten magmas and through metamorphic processes. The various modes of occurrence will be mentioned for the various kinds.

Tremolite and *actinolite* are known only as secondary or metamorphic minerals. They do not appear to crystallize directly from molten magmas. Their chief occurrence is in the crystalline schists and in granular or massive metamorphic rocks. They are also common products of alteration in igneous rocks.

In metamorphic rocks they usually form thin prismatic crystals scattered in all directions or clustered in more or less radiating groups. In dimensions they range from microscopic sizes to large megascopic ones. They may be associated with other minerals, or form the chief constituent of the rock. Tremolite is oftenest developed in metamorphosed magnesian limestones, being frequently associated with calcite. It also occurs in serpentine associated with olivine and pyroxene as an alteration product, in peridotites, and in some gabbros. Actinolite is the commoner variety of the two, being wide-spread in various schists and massive metamorphic rocks. It is frequently a secondary mineral in igneous rocks, resulting from the alteration of pyroxenes and hornblende. In some instances the actinolite needles lie at various angles in confused aggregation, in others they are all parallelly oriented, and the *c* and *b* axes of the amphibole are parallel to these axes in the original pyroxene crystal. Such secondary amphibole often retains the outward shape of the former pyroxene, becoming a pseudomorph after it. It is usual for the twinning of the pyroxene, when present, to be reproduced in the fibrous or prismatic amphibole, and in some instances the pinacoidal parting of diallage is maintained in the secondary mineral. Such actinolite pseudomorphs after diallage have been called *smaragdite*. They occur in certain altered gabbros, together with saussurite. The more or less fibrous pseudomorph of amphibole after pyroxene is called *uralite* and may have the composition of actinolite or of common hornblende, according to the composition of the original pyroxene. Tremolite and actinolite also occur in finely fibrous masses, *asbestus*, and in dense, aphanitic to megascopically fine-grained masses called *nephrite*. *Grünerite* has much the same mode of occurrence as actinolite, but is much less common. It is found in mica-schist near Collobrières, France, and in association with iron ores in the Lake Superior region.

Edenite, the aluminous amphibole poor in iron, occurs in crystalline limestone with other silicates in the manner of minerals produced by contact metamorphism. It is comparatively rare. *Pargasite* is found in metamorphic rocks, both in gneisses and crystalline limestone. It is much less common than ordinary hornblende.

Common hornblende occurs both in igneous and in metamorphic rocks. In igneous rocks it is a common constituent of various phanerocrystalline rocks—granite, syenite, diorite, gabbro, etc.—and also of many aphanitic and glassy ones. But it is more frequently developed in the phanerocrystalline rocks than in the chemically equivalent lavas. In porphyritic rocks it is oftener crystallized as phenocrysts than as microlites in the groundmass. It sometimes is a secondary mineral in igneous rocks resulting from the alteration of pyroxene. Occasionally it is compact and is scarcely to be distinguished from pyrogenetic hornblende. The only unquestionable means of distinguishing it is the retention of a pyroxene outline, demonstrating its pseudomorphous character, or its occurrence in veins traversing primary, pyrogenetic, minerals like feldspar in a manner not possible with pyrogenetic hornblende. In metamorphic rocks it forms a constituent of many gneisses and of some schists, being almost the sole component of certain amphibolites.

Basaltic hornblende occurs wholly in igneous rocks and grades into common hornblende. It occurs in the same manner so far as crystal forms and textures of rocks are concerned, but is developed in magmas of somewhat different composition, namely, those with more iron. The two varieties, however, crystallize in the same rock in some instances, occasionally as parts of one and the same crystal. It is more common in gabbros, basalts, and rocks of closely similar composition than in diorites or granites. It grades into more alkalic varieties rich in ferric oxide, and through these into barkevikite, and therefore occurs in the same kinds of magmas.

Barkevikite and *katoforite* occur wholly in igneous rocks distinctly alkalic, generally rich in soda; especially in nephelite-syenite and syenites and related porphyries in Norway, and in similar petrographic provinces in other parts of the world. *Arfvedsonite* is likewise a constituent of alkalic igneous rocks rich in soda, and is associated with barkevikite. It is best developed in the nephelite-syenites of Greenland. *Riebeckite* is developed in certain granites and syenites rich in alkalies with abundant soda, and to a less extent in porphyries and lavas of similar composition. *Hastingsite* is found in nephelite-syenite from Dunganon, Hastings County, Ontario. *Glaucophane* is a constituent of metamorphic rocks only, occurring in mica-schists and other schistose rocks, in eclogite and in crystalline limestone. The occurrence of gastaldite is similar. *Crossite* forms a rock with albite in the crystalline schists near Berkeley, Cal.

Resemblances.—Monoclinic amphiboles are most nearly like monoclinic pyroxenes in optical properties, having nearly the same refraction and double refraction, and in some varieties similar colors. But they differ distinctly in the angle of prismatic cleavage and of crystal outline in cross-section. In general the angle of extinction in longitudinal sections reaches higher values in pyroxenes than in similarly colored amphiboles. Colorless and pale, non-pleochroic amphiboles, tremolite, actinolite, edenite, differ from colorless or pale diopside in the cleavage and cross-section, lower maximum of extinction angles, $Z \wedge c$ about 15° in the amphiboles and about 30° in diopside. They may be distinguished from sillimanite, which they closely resemble in form and refraction, by the orthorhombic character of this mineral, $Z \wedge c = 0°$. They differ from wollastonite by the angles of cleavage, the zero angle of extinction in prisms of wollastonite parallel to b, in which $Y \parallel b$, and in the positions of the plane of the optic axes, which in the latter mineral is at right angles to the planes of cleavage (100) (001).

Pale pleochroic actinolite is distinguished from epidote by the stronger double refraction of the epidote and its slightly higher refraction; the position of the plane of the optic axes, which is normal to the planes of cleavage, and the prism axis of the epidote crystals, parallel to b with $Y \parallel b$.

Hornblende because of its marked pleochroism and colors is easily distinguished from minerals which have nearly the same refraction and double refraction. It is distinguished from ægirite and acmite, which resemble it somewhat in color and pleochroism, by the angle of the prismatic cleavage and of the outline of cross-section, and by the fact that the bisectrix nearest c is Z in hornblende and X in ægirite and acmite. Brown hornblende and brown pleochroic allanite are distinguished by the cleavage and the optical orientation of allanite, which is the same as that of iron-epidote previously mentioned. Hornblende often resembles sections of similarly colored mica cut parallel to the cleavage. The mica is identified by the complete absence of cleavage in such sections, and its small optic axial angle, approaching that of a uniaxial mineral.

The pleochroic amphiboles of various colors somewhat resemble tourmaline in refraction, double refraction, and colors, but they are distinguished by the uniaxial character of the tourmaline in cross sections, the parallel extinction in prismatic sections of tourmaline, by the absence of cleavage, and the stronger absorption in tourmaline of light vibrating across the prism, $O > E$.

The bluish amphiboles resemble few other rock-making minerals. Dumortierite approaches them in refraction and pleochroism, but has lower double refraction and is orthorhombic.

Laboratory Production.—Amphibole has only been produced in the laboratory upon one occasion, when von Chrustschoff obtained small crystals about 1 mm. long by 0.25 mm. thick after three months' exposure of the chemical constituents in the presence of water in a closed vessel to a temperature of 550° C. The resulting mineral exhibited the physical properties of an amphibole, but its exact chemical composition was not determined.

ÆNIGMATITE (Cossyrite).

$$Na_4Fe_9^{III}AlFe(Si,Ti)_{12}O_{38}.$$

Triclinic. $a:b:c=0.6778:1:0.3506$. $\alpha=90°$, $\beta=72°\,49'$, $\gamma=90°$ approx. *Twinning* plane (010), common.

Cleavage: (110) ($1\bar{1}0$) distinct, with angle of 66° approx. Fracture uneven. H. =5.5. Sp. gr. =3.80–3.85 for ænigmatite, 3.74–3.75 for cossyrite.

Optical Properties.—Axial plane nearly parallel to (010). The acute bisectrix is Z, optically positive (+), and $Z \wedge c=45°$ approx., $2E=60°$ approx. Index of refraction about the same as for monoclinic amphibole; double refraction low, $\gamma-\alpha=0.0064$.

Color: black, reddish brown in very thin sections. Pleochroism strongly marked. Streak reddish brown. *Luster:* vitreous.

Chemical Composition.—A titanosilicate of iron and sodium with some aluminium and smaller amounts of manganese, calcium, and magnesium. The analysis of ænigmatite from Greenland shows considerable TiO_2, which does not appear in that of cossyrite from Pantellaria, but which may possibly be present.

	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	MnO	CuO	
Ænigmatite	37.92	7.57	3.23	5.81	35.88	0.33	1.36	6.58	0.51	1.00	—	=100.19
Cossyrite	43.55	—	4.96	7.97	32.87	0.86	2.01	5.29	0.33	1.98	0.39	=100.21

Partially decomposed by acids. Alterations and decomposition products not definitely known. Supposed by Hackman to alter to a fibrous or acicular mineral whose composition has not been determined.

Crystal Form.—The habit is prismatic like amphibole, but the prismatic angle (110) $\wedge$ ($1\bar{1}0$) is 66°. The forms observed are (110), ($1\bar{1}0$) dominant, (100) and (010) subordinate, besides a number

of well-developed planes terminating the prism (011), (0$\bar{1}$1), (031), (0$\bar{3}$1), and others. The twinning parallel to (010) is sometimes repeated, producing twinned lamellæ. It occurs also in anhedral and rounded shapes. Ænigmatite crystals in Greenland sometimes reach lengths of several inches. The dimensions of cossyrite are small. The prismatic cleavage is very distinct in cross section and in those near (010).

Optical Properties.—Owing to the very strong absorption in several directions little has been positively determined regarding the optical constants. The plane of the optic axes lies nearly parallel to (010). The acute bisectrix Z is inclined about 45° to c. In sections parallel to (100) the extinction angle is 3° 46′ from the c axis. In sections parallel to (010) it is 44° 57′ (Fig. 1). The corresponding measurements on cossyrite are 3° and 39°. The index of refraction is somewhat near that of amphibole; the double refraction is lower, $\gamma-\alpha=0.0064$. The angle between the optic axes is rather low, $2E=60°$ approx. Dispersion of the optic axes not distinct, apparently $\rho<v$. The interference figure about the acute bisectrix exhibits unsymmetrical dispersion.

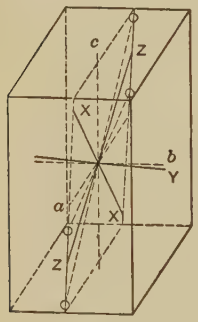


FIG. 1.

Color.—In ordinary sections nearly opaque; in extremely thin sections brown to black, according to the position of the section. Absorption and pleochroism very pronounced in all sections except in that parallel to (100). Z, brown-black; Y, deep chestnut-brown; X, clear red-brown. $Z>Y>X$, as in hornblende.

Modes of Occurrence.—Ænigmatite occurs in megascopic crystals in nephelite-syenite at Naujakasik near Kangerdluarsuk in Greenland, associated with arfvedsonite and ægirite. It has also been found in nephelite-syenite on the Kola peninsula, and to some extent in closely related rocks in other regions. Cossyrite occurs in minute crystals associated with other alkalic amphibole and ægirite in pantellerite on Pantellaria.

Resemblances to Other Minerals.—Ænigmatite resembles to some extent the darker-colored basaltic hornblendes and allanite, but it is distinguished from these minerals by its great absorption, which is almost complete for all rays but red, and also by its low double refraction and its cleavage.

GARNET GROUP.

$$\overset{II}{R}_3\overset{III}{R}_2(SiO_4)_3 \quad \text{or} \quad 3RO \cdot R_2O_3 \cdot 3SiO_2.$$

$\overset{II}{R}$ = Ca, Mg, Fe, Mn. $\overset{III}{R}$ = Al, Fe, (Mn), Cr, Ti.

Garnets are orthosilicates with the general formula $\overset{II}{R}_3\overset{III}{R}_2(SiO_4)_3$, in which $\overset{II}{R}$ and $\overset{III}{R}$ may be one or more of the elements indicated above. In some cases Ti replaces Si. The group forms an isomorphous series of compounds varying considerably in composition which has been divided into a number of varieties, the principal ones being expressed by simplified formulas as follows:

Grossularite (hessonite)	$Ca_3Al_2(SiO_4)_3$.
Pyrope	$Mg_3Al_2(SiO_4)_3$.
Almandite	$Fe_3Al_2(SiO_4)_3$.
Spessartite	$Mn_3Al_2(SiO_4)_3$.
Andradite (melanite)	$Ca_3Fe_2(SiO_4)_3$.
Also	$(Ca,Mg)_3Fe_2(SiO_4)_3$
and	$Ca_3Fe_2((Si,Ti)O_4)_3$.
Schorlomite	$Ca_3(Fe,Ti)_2((Si,Ti)O_4)_3$.
Uvarovite	$Ca_3Cr_2(SiO_4)_3$.

In each of these simple molecules there are small amounts of the other isomorphous molecules. This is shown by analyses from a few of the many known occurrences, most of those selected having been studied optically.

Alteration.—Most garnets are not decomposed by acids; some varieties are partially decomposed. The garnets with simpler molecules are seldom found in an altered condition in rocks. They sometimes alter to chlorite or serpentine. But common garnet, which contains Ca, Fe, Mg in considerable amounts, is known to alter into a number of minerals, of which the commonest is chlorite; less frequently it alters to hornblende. In amphibole-schists of the Stamser Alps it has been changed to scapolite, epidote, oligoclase, hornblende, saussurite, and chlorite. (Cathrein.)

Crystal Forms.—Isometric system. Euhedral crystals commonly dodecahedrons $d(110)$ and icositetrahedrons $n(211)$, or these in combination, Figs. 1, 2, and 3, also with (321). Rarely in octahedrons (Elba). Dodecahedral faces sometimes striated parallel to the

ANALYSES OF GARNET.

		Sp. gr.	SiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	H_2O	TiO_2	Cr_2O_3	
Grossularite.	theoretical	—	40.0	22.7	—	—	—	—	37.3	—	—	—	—	100.0
1. Wakefield	white	3.525	38.80	22.66	1.75	—	0.30	0.68	35.00	—	—	—	—	99.19
2. Auerbach	"	3.47	41.80	20.91	—	2.01	0.18	0.82	33.48	0.42	0.38	—	—	100
3. Cziklowa,	yellow	3.571	39.74	19.23	—	5.14	0.13	0.56	35.48	0.61	0.53	—	—	101.42
4. Mussa Alp, Ala	brown	3.633	38.12	18.35	7.17	—	0.13	0.02	35.40	0.42	0.74	—	—	100.35
Pyrope.	theoretical	—	44.8	25.4	—	—	—	29.8	—	—	—	—	—	100.0
5. Kimberly	wine-red	—	41.34	22.75	—	12.12	0.36	16.20	5.17	—	—	—	2.96	100.90
6. "	hyacinth-red	—	40.90	22.81	—	13.34	0.38	16.40	4.70	—	—	—	1.48	100.04
Almandite.	theoretical	—	36.2	20.5	—	43.3	—	—	—	—	—	—	—	100.0
7. Wittichen	dark red	3.96	37.40	21.08	2.01	28.49	—	8.22	3.05	—	—	—	—	100.25
8. Ft. Wrangel, Alaska		4.093	39.29	21.70	tr.	30.82	1.51	5.26	1.99	—	—	—	—	100.57
9. Salida, Colo.	red	4.163	37.61	22.70	—	33.83	1.12	3.61	1.44	—	—	—	—	100.31
Spessartite.	theoretical	—	36.4	20.6	—	—	43.0	—	—	—	—	—	—	100.0
10. Haddam	reddish brown	4.273	36.16	19.76	—	11.10	32.18	0.22	0.58	—	—	—	—	100.00
Uvarovite.	theoretical	—	35.9	—	—	—	—	—	33.5	—	—	—	30.6	100.00
11. Bissersk	emerald-green	3.418	37.11	5.88	—	2.44	—	1.10	30.34	—	1.01	—	22.54	100.42
Andradite.	theoretical	—	35.5	—	31.5	—	—	—	33.0	—	—	—	—	100.0
12. Sisersk, demantoid	green	3.828	35.56	0.57	30.80	0.64	—	0.16	33.05	—	—	—	—	100.78
13. East Rock, New Haven	black	3.740	35.09	tr.	29.15	2.49	0.36	0.24	32.80	—	0.35	—	—	100.48
14. Frascati	"	3.77	35.09	8.80	19.27	1.80	—	0.47	32.61	—	—	3.02	—	101.06
Schorlomite.														
15. Magnet Cove, Ark.	"	3.783	26.09	—	20.11	1.57	—	1.36	29.38	—	—	21.34	—	99.85

longer diagonal. Anhedral crystals often rounded or irregularly formed, in grains or granular aggregates. Sometimes most irregularly shaped.

Twinning plane (210) rare.

Cleavage or parting parallel to (110) sometimes distinct, seldom observed in garnets in rock sections, possibly due in part to zonal structure. Fracture subconchoidal to uneven. H. = 6.5–7.5.

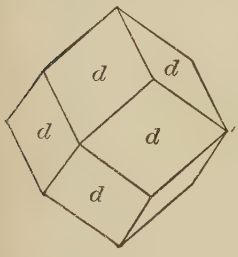


Fig. 1.

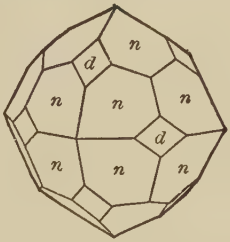


Fig. 2.

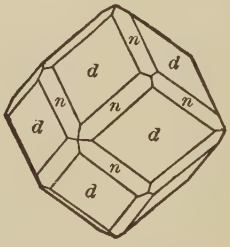


Fig. 3.

Sp. gr. = 3.15–4.3, varying with the composition, as shown for specific cases mentioned in the table of chemical analyses.

Optical Properties.—Isotropic in most cases. Many garnets exhibit anomalous double refraction which is usually weak, but may reach 0.010. The double refraction is often variable in different parts of one crystal, having a definite relation to the form or to definite crystal faces. Such crystals are composed of pyramidal parts, the base of a pyramid being a crystal face, the apex the center of the crystal. Each part has a definite optical orientation. A number of different types of these arrangements have been recognized according to the plane of the crystal serving as base of the pyramidal part. The cause of the double refraction has been the subject of much speculation and investigation, a detailed statement of which will be found in Rosenbusch and Wülfing's Mikroskopische Physiographie. Mallard and Bertrand attributed the phenomena to the complex twinning of triclinic crystals. Klein has shown that the distribution of the double refraction is directly related to the outward form of the crystal and is in fact a secondary molecular condition probably due to contraction after crystallization. Brögger has called attention to the fact that the pyrogenetic garnets in igneous rocks are always isotropic, while the doubly refracting ones occur in cavities or in zones of contact metamorphism, where they may have crystallized from hot aqueous solutions. The index of refraction is high, varying with the composition of the garnet as shown by Wülfing in the following table. The chemical analyses of

most of the garnets mentioned are given in the table of chemical analyses.

			n_{li}	n_{na}	n_{tl}	$n_{tl} - n_{li}$	
Grossularite	Wakefield	colorless	1.7394	1.7438	1.7480	0.0086	W.
"	Auerbach	reddish tint	1.7399	1.7441	1.7482	0.0083	W.
"	Cziklowa	weak yellow	1.7520	1.7569	1.7617	0.0097	W.
Hessonite	Ala	brown	1.7575	1.7626	1.7676	0.0101	W.
Pyrope	Kimberley	wine-red	1.7369	1.7412	1.7451	0.0082	W.
"	"	brownish yellow	1.7396	1.7439	1.7479	0.0083	W.
"	"	hyacinth-red	1.7459	1.7504	1.7545	0.0086	W.
"	Meronitz	wine-red	1.7420	1.7464	1.7505	0.0083	W.
Almandite	Wittichen	dark red	1.8022	1.8078	1.8125	0.0103	W.
"	Orient	" "	1.8052	1.8109	1.8159	0.0107	W.
Spessartite	Haddam	reddish brown	1.8050	1.8105	1.8158	0.0108	W.
Uvarovite	Bissersk	emerald-green	1.8318*	1.8384	1.8449	0.0132	W.
Melanite	Frascati	black	1.8467	1.8566	1.8659	0.0183	W.
Demantoid	Syssersk	green	1.8780	1.8893	1.9005	0.0225	O.

W. = Wülfing; O = Osann.

* Determined with eosine liquid instead of lithium flame.

Color.—Variable according to the composition. In *grossularite* white, pale green, yellow, brownish yellow, cinnamon-brown, pale rose-red; rarely emerald-green, from chromium. *Pyrope:* deep red to nearly black. *Almandite:* deep red, brownish red, black. *Spessartite:* hyacinth-red, sometimes with a tinge of violet, brownish red. *Andradite:* wine-, topaz-, and greenish yellow, apple-green to emerald-green, brownish red, brownish yellow, grayish green, dark green, brown, grayish black, black. *Uvarovite:* emerald-green. *Schorlomite:* black. Luster, vitreous to resinous. Asterism sometimes exhibited by zonally built crystals. Zonal structure is commonly developed; crystals varying in composition and color in concentric shells or zones, frequently associated with anomalous double refraction.

Modes of Occurrence.—Garnets are of wide-spread occurrence, being found in all kinds of rocks. But certain varieties have more or less restricted range. The variety of garnet developed in a rock usually bears some relation to the chemical composition of the rock.

Grossularite is chiefly found in metamorphosed limestones, lime-silicate-hornfels, and in the crystalline schists. It is associated with vesuvianite, wollastonite, diopside, and other calcium-silicates, and is often crowded with inclusions of the other minerals in the rock.

Pyrope is developed in basic igneous rocks, the peridotites, and is also found in serpentines derived from them. It is often sur-

rounded by a shell of other minerals, called a *kelyphite*. In cross section the shell appears as a zone or rim of prismatic or fibrous crystals lying perpendicular to the pyrope. There is sometimes a granular outer portion. The composition of this kelyphite rim differs in different cases. In some it consists of prisms of hornblende and picotite grains; in others of monoclinic pyroxene, or bronzite and picotite. The formation of the fibrous shell has been accounted for upon several hypotheses; one that it is subsequent to the solidification of the rock, due to a chemical reaction between the pyrope and adjacent olivine during dynamic metamorphism of the rock. Another hypothesis is that a reaction between pyrope and olivine took place while the magma was still in part molten, due to change of molecular stability caused by change of pressure while the magma was being erupted.

Almandite occurs in granites and some andesites, but is more common in gneiss, granulite, and schists. It often contains abundant inclusions of the minerals associated with it, and is sometimes intergrown with pyroxene, hornblende, and quartz.

Common garnet, containing grossularite, almandite, and andradite molecules, is a common constituent of the crystalline schists, amphibolites, eclogite, pyroxene rocks, and others derived from them, as well as in the phyllites; in certain garnet rocks and metamorphosed gabbros. It often abounds in inclusions of the minerals associated with it, and in fluid inclusions. It is sometimes graphically intergrown with other minerals.

Spessartite is crystallized to some extent in granite; occurs in cavities with topaz in rhyolite at Nathrop, Colo., and in Utah. It is abundant in the whetstone schists of Belgium, and also occurs in metamorphosed quartzites of the Taunus and the Ardennes.

Andradite.—The black variety, *melanite*, dark brown in thin section, is a common constituent of the alkalic igneous rocks, nephelite-syenite, phonolites, leucitic and nephelitic lavas. The melanite in the peperin of Frascati has a colorless central core of crystallographically bounded garnet. *Titaniferous melanite* also occurs in these alkalic igneous rocks, having been found in phonolite at Oberschaffhausen and also on the Kaiserstuhl, and in leucitophyre at Horberig near Oberbergen.

Schorlomite, closely related to titaniferous melanite, is found with this mineral in the nephelite rocks at Magnet Cove, Ark. The similar variety *iivaarite* occurs in a nephelite rock, iiolite, at Iiwaara in Finland.

Demantoid, a bright-green variety of andradite, is found in serpentine in the Ural Mountains and elsewhere. It is sometimes composed of green and brown zones.

Uvarovite is rare, occurring with chromite in serpentine at Bissersk, and in crystalline limestone and dolomite at Orford, Canada.

Resemblances.—Garnets are most like the spinels in optical characters. They are much commoner minerals and usually occur in larger crystals. Those varieties of each that are most alike can only be distinguished by chemical means. The garnets yield SiO_2.

Laboratory Production.—Garnet has been produced with difficulty in the laboratory. Spessartite has been formed by fusion of its constituents in magnesium chloride. Melanite has been formed in the open crucible with other constituents of nephelinite, as in igneous rocks. It has also been formed by fusing in a graphite crucible ilmenite, calcium sulphide, silica, and charcoal at a temperature of 1200° C. Ordinarily when garnet is fused it breaks up on crystallization into other compounds such as pyroxene, melilite, monticellite, scapolite, anorthite.

OLIVINE GROUP.

R_2SiO_4.

Forsterite	Mg_2SiO_4.
Olivine	$(Mg,Fe)_2SiO_4$.
(Chrysolite)	
Hortonolite	$(Fe,Mg,Mn)_2SiO_4$.
Fayalite	Fe_2SiO_4.
Titanolivine	
Monticellite	$CaMgSiO_4$.
Tephroite	Mn_2SiO_4.
Roepperite	$(Fe,Mn,Zn)_2SiO_4$.

The olivine group is a closely isomorphous series of orthosilicates with the general formula R_2SiO_4, in which R = Mg, Fe, less often Ca, Mn, and Zn. The magnesium-iron compounds are commonest in igneous rocks, but also occur in metamorphic rocks. The calcium, manganese, and zinc compounds are developed chiefly in metamorphosed limestones.

They crystallize in the orthorhombic system, in crystals of nearly the same habit, with nearly the same axial ratios, and similar physical properties.

Chemical Composition. — Forsterite and olivine grade into one another chemically; a small amount of FeO may be present in forsterite, up to 4.56 per cent, while olivine may contain only 5 per cent of FeO. Between olivine with 30 per cent of FeO and fayalite with 63 per cent there are no intermediate varieties in rocks yet analyzed. The following are some of the analyses:

Forsterite.	Sp.gr.	SiO_2	MgO	FeO	Ign.	CaO	Al_2O_3	Fe_2O_3	
Theoretical	—	42.9	57.1	—	—	—	—	—	=100.00
Ural	3.191	40.11	57.73	0.22	0.16	—	—	1.8	= 99.40
									Na_2O K_2O
Mte. Somma	—	41.85	56.17	1.07	0.19	—	—	—	0.12 0.40
									= 99.80
Bolton, Mass.	3.21	42.82	54.44	1.47	0.76	0.85	—	—	=100.34
Kaiserstuhl	—	41.88	49.83	4.56	2.00	$+Al_2O_3$,etc.		MnO 1.73	
									=100.00
Olivine.									
Vesuvius	3.261	42.30	51.64	5.01	—	1.08	0.42		=100.45
Webster, N. C.	3.266	41.17	49.16	7.35	0.69	0.04	NiO 0.41,		insol. 1.23
									=100.05
Elliot Co., Ky.	3.377	40.05	48.68	7.14	0.80	1.16	TiO_2 0.07,		P_2O_5 0.04,
	Fe_2O_3 2.36,		Cr_2O_3 0.24,		Al_2O_3 0.39,		MnO 0.20,		Alk 0.29= 99.42
Etna	—	41.06	46.83	10.13	Al_2O_3 0.68,		H_2O 1.33		=100.03
Vesuvius	—	39.85	49.19	10.54					= 99.58
Hawaii	—	40.01	48.09	11.12	TiO_2 0.12,		Ni(Co)O 0.22,		
									$Al(Fe)_2O_3$ 0.49= 99.88
Vesuvius	—	40.35	46.70	12.34					= 99.39
Ste. Anne	—	38.56	44.37	12.65	Fe_2O_3 1.36,		Mn(Co)O 0.11.		
									ign. 2.91= 99.96
Montarville	—	37.17	39.68	22.54					= 99.39
Waterville, N. H.	—	38.85	30.62	28.07	MnO 1.24,		CaO 1.43		=100.21
Kaiserstuhl	3.566	36.72	31.99	29.96					= 98.67
Fayalite.									
Yellowstone Park	—	32.41	—	65.49	MnO 2.10				=100.00
Theoretical	—	29.4	—	70.6					=100.00
Titanolivine.									
Pfunders	3.25	36.30	49.65	6.00	MnO 0.60,		TiO_2 5.30,		ign. 1.75
									= 99.60
Zermatt	3.27	36.14	48.31	6.89	MnO 0.19,		TiO_2 6.10,		ign. 2.23
									= 99.86

The small amounts of various elements found in the analyses and not belonging properly to the olivine minerals are due to inclusions, such as magnetite, spinel, etc.

Alteration.—Decomposed by hydrochloric acid with separation of gelatinous silica. Olivine and fayalite are readily altered to other

minerals. *Fayalite* changes upon exposure to atmospheric agencies to ferric oxide and silica. The alteration takes place from the surface of the crystal, producing an opaque crust which eventually replaces the entire mineral. The fayalite in the pegmatite at Rockport, Mass., is altered to anthophyllite. Olivine alters by several processes. The commonest is into a network of fibrous or scaly serpentine and iron oxide. The alteration sets in from the exterior of the crystal and from cracks, the serpentine fibers developing normal to these surfaces. The separated iron oxide, magnetite, hematite, or hydrous oxide, goethite, or limonite, is deposited along the cracks, producing a net-like arrangement which is very characteristic of this mode of alteration of olivine. The development of lamellar serpentine, antigorite, parallel to the surfaces of cracks and the exterior of the crystals, has been noted in olivine from dunite at several localities in the Stubachthal; in the vicinity of Prägraten and in Norrland, Sweden.

Another very common mode of alteration is to a red lamellar mineral, iddingsite. In this case the secondary mineral develops from cracks on the exterior of the crystal in laminæ which are parallelly oriented, possibly in the plane of (100) or (010) of the olivine (Fig. 1), so that the resulting product is a homogeneous crystal,

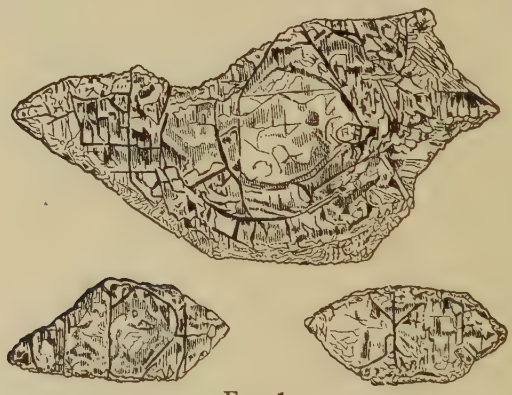


Fig. 1.

the exact nature of which is still in doubt. It is probably a variety of serpentine, possibly antigorite, submicroscopically interlaminated with hematite, with the acute bisectrix X and the optic axes of the hematite parallel to one another. In some instances iddingsite begins to develop at the center of the olivine. This very common method of alteration often takes place in basalts exposed to the

atmosphere, as in the Eureka District, Nev., on Mt. Norris, Yellowstone Park; also in carmeloite, Carmelo Bay, Cal.; in olivine-tholeite in Derbyshire, Eng., and elsewhere.

Olivine also alters to spherulitic aggregations of chloritic character, which have been considered to be delessite, grengesite, or chlorophæite. The end product of weathering may be an aggregation of iron oxide, silica in the form of quartz or opal, and carbonates both of magnesium and calcium. Changes of olivine to amphibole are less frequent; the result in some cases is a mass of amphibole needles with admixture of other alteration products. This has been called pilite by Becke. Olivine has also altered to pyroxene in some serpentines, as in the Stubachthal, Tyrol, and elsewhere. Changes of olivine which appear to have taken place before the final consolidation of the rocks are those that have produced kelyphite-like shells of amphibole about crystals of olivine in certain gabbros in Sweden.

Orthorhombic.—Forsterite, Olivine } $a:b:c=0.4656:1:0.5865$
Fayalite " $=0.4584:1:0.5793$
Monticellite " $=0.4337:1:0.5758$
Tephroite " $=0.4600:1:0.5939$

Crystals often flattened parallel to $a(100)$ or $b(010)$, less often elongated parallel to the c axis. Euhedral crystals bounded by prisms of the first, second, and third kind, and by bipyramids. The simpler combinations in olivine are shown in Figs. 2, 3, and 4, with

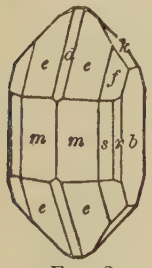


FIG. 2.

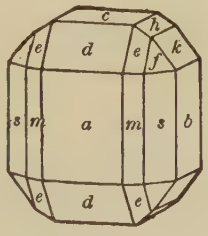


FIG. 3.

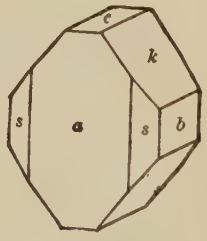


FIG. 4.

$a(100)$, $b(010)$, $c(001)$, $m(110)$, $s(120)$, $r(130)$, $h(011)$, $k(021)$, $d(101)$, $e(111)$, $f(121)$. The crystals of fayalite are somewhat more tabular parallel to $a(100)$, Figs. 5 and 6. The crystals of other varieties are similar in habit and forms to those of olivine.

Anhedral crystals are common as irregularly shaped or rounded grains. Skeleton forms resulting from rapid growth occur in some

lavas, as in the basalt of Hawaii, Figs. 25, p. 62, and in the lavas of Vesuvius, Fig. 7.

Twinning rare. In olivine (1) twinning plane $h(011)$ with the c axes at 60° 47′, penetration twins, sometimes repeated to form

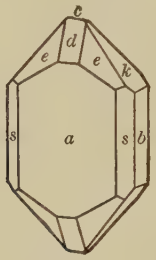


Fig. 5.

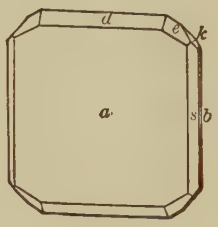


Fig. 6.

stellate trillings; (2) twinning plane parallel to $s(012)$, with the c axes at 32° 41′; (3) twinning plane (031) with the c axes at 59° 50′.

Cleavage parallel to $b(010)$ distinct, to somewhat distinct in olivine; parallel to $a(100)$ in olivine less so; in forsterite indistinct parallel to $c(001)$. Fracture conchoidal in olivine; subconchoidal to uneven in the others. H. = 6–7 in forsterite, 6.5–7 in

Fig. 7.

olivine, 6.5 in fayalite, 5–5.5 in monticellite, 5.5–6 in tephroite. Sp. gr. = 3.03–3.25, monticellite; 3.21–3.33, forsterite; 3.27–3.37, olivine; 3.57, hyalosiderite; 4–4.14, fayalite; 4–4.12, tephroite.

Optical Properties.—Plane of the optic axes parallel to (001); $X \parallel b$, $Y \parallel c$, $Z \parallel a$. In forsterite and olivine, with less than 12 per cent of FeO, Z is the acute bisectrix. The crystals are optically positive (+), Fig. 8. In olivine with more than 12 per cent of FeO, and in fayalite, hortonolite, monticellite, and tephroite, X is the acute bisectrix and the crystals are optically negative (−), Fig. 9. Optic angle large, varying with the chemical composition, as shown by

the accompanying table compiled by Penfield and Forbes, to which have been added several other observations.

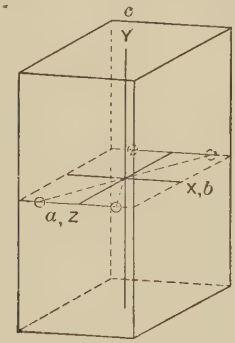


FIG. 8.

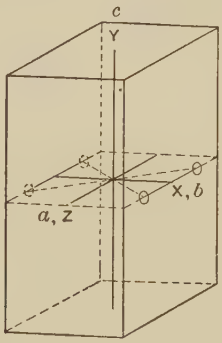


FIG. 9.

	FeO.	$2V_y$ on X.	β_y	Character.		Dispersion.
Forsterite, Vesuvius	—	93° 50′	1.659	+	$\rho<v$	
Olivine, East India	—	92° 45′	1.670	+		
" (?)	—	92° 14′	1.678	+		
(" Koswinsky	8.2	94° calc.	1.6707	+	$\rho<v$	Duparc & Pearce)
" New Mexico	8.6	91° 24′	—	+		
" Egypt	9.2	91° 19′	1.678	+		
" Hawaii	10.3	91° 2	—	+		
(" Koswinsky	10.7	92°	1.6899	+	$\rho<v$	Duparc & Pearce)
" Vesuvius	12.6	89° 42′	—	−		
" Auvergne	13.0	89° 36′	1.692	−		
Hortonolite, Monroe	47.3	69° 24′	1.791	−	$\rho>v$	
Fayalite, Rockport	68.1	49° 50′	1.864	−	$\rho>v$	
(Monticellite, Magnet Cove	—	37° 31′	1.6616	−	$\rho>v$	Penfield & Forbes)
(Tephroite, Pajsberg	—	76° 6′	—	−	$\rho>v$	Flink)

The dispersion is in the same direction in all cases, being $\rho<v$ for positive crystals and $\rho>v$ for negative ones.

Forsterite, Mte. Somma	$2V_r = 86° 1′$	$2V_y = 86° 10′$	$2V_{bl} = 86° 32′$ Des Cloizeaux
" " "	$= 85° 35′$	$= 85° 41′$	$= 85° 54′$ Arzruni
Olivine, Torre del Greco	$2H_r = 105° 58′$	$2H_y = 106° 21′$	$2H_{bl} = 107° 14′$ Des Cloizeaux
Fayalite, Rockport	$= 57° 27′$	$= 56° 32′$	$= 55° 2′$ Penfield & Forbes
Monticellite, Magnet Cove	$2V_r = 37° 51′$	$2V_y = 37° 31′$	$2V_{gr} = 36° 28′$ Penfield & Forbes
Titanolivine	$2V_y = 62° 18′$		

Refraction moderately high to high, double refraction strong except in monticellite, in which it is moderate.

	α_y	β_y	γ_y	$\gamma-\alpha$	
Monticellite, Magnet Cove	1.6505	1.6616	1.6679	0.0174	Penfield & Forbes
Forsterite	—	1.659	—	—	—
Olivine, East India	1.6535	1.6703	1.6894	0.0359	Zimanyi
" Koswinsky	1.6543	1.6707	1.6896	0.0353	Duparc & Pearce
" "	1.6720	1.6899	1.7089	0.0369	"
" —	1.661	1.678	1.697	0.036	Des Cloizeaux
Hortonolite, Monroe	1.7684	1.7915	1.8031	0.0347	Penfield & Forbes
Fayalite, Rockport	1.8236	1.8641	1.8736	0.0500	"
Titanolivine	1.669	1.678	1.702	0.033	Lacroix

Color.—In most varieties yellows or greens, in tephroite red. *Forsterite:* white, yellowish, grayish, bluish, greenish; in thin sections colorless. *Olivine:* green, olive-green, sometimes brownish, grayish red, grayish green, becoming yellowish brown or red on oxidation of the ferrous iron; in thin section colorless to greenish; not pleochroic. *Hortonolite:* yellow to dark yellowish green on fresh fracture, but black and dull on exposed surface. *Titanolivine:* brownish red; strongly pleochroic; X deep reddish yellow, $Y=Z$ bright yellow; absorption, $X>Y>Z$. *Fayalite:* light yellow, becoming black and opaque on exposure; in thin section colorless to yellowish; slightly pleochroic; $X=Z$ greenish yellow, Y orange-yellow, in thick plates. *Monticellite:* colorless, yellowish gray, pale greenish, and whitish; in thin section colorless. *Tephroite:* grayish flesh-red, reddish brown, rose-red, ash-gray to smoky gray; darkens on exposure to brown and black; pleochroism distinct; X brownish red, Y reddish, Z greenish blue; $Y>Z>X$. Luster vitreous; slightly resinous in monticellite, to greasy in tephroite.

Inclusions.—Olivine and the other minerals of this group are commonly quite free from inclusions or, rather, possess no especially characteristic ones. Olivine incloses occasional crystals of spinel, magnetite, ilmenite, or apatite, and sometimes glass or fluid inclusions. In gabbros the olivine sometimes is clouded with innumerable microscopic rods and blades, probably of ilmenite. In the olivine of some basalts these tabular microlites are regularly intergrown parallel to (100), the two minerals in some cases forming a regular network.

Occurrence.—*Olivine* is commonly developed in the less siliceous igneous magmas, especially in the lava forms. Thus it occurs in peridotites and some gabbros; in limburgites and basalts; in many nephelite and leucite rocks, both phanerocrystalline and aphanitic.

It is found to a much less extent in some trachytes, andesites, and even dacites. Its composition varies with that of the magma, but to exactly what extent is not yet known. In those magmas low in iron the olivine is also low in iron, and hyalosiderite and fayalite crystallize from magmas low in magnesium, as the fayalite described by Weidman in a nephelite-syenite from Wisconsin. *Fayalite* occurs in lithophysæ and porous spherulites or in cavities in rhyolite, as the result of the action of vapors within the cavities at the time of the consolidation of the rock, as in rhyolites of the Yellowstone Park, Mexico, Lipari, and elsewhere. Fayalite also occurs in granitic pegmatites in the Mourne Mountains, Ireland, and at Rockport, Mass. *Olivine* is developed in metamorphosed magnesian limestones and in some amphibolites and pyroxene rocks and talc schists. *Forsterite* occurs in limestone metamorphosed by contact with igneous rocks, as in ejected blocks on Mte. Somma, at the crater of Baccano, Albani Mountains; in the vicinity of intruded rocks, as at Kaiserstuhl and in Ariège in the Pyrenees; and in crystalline limestone at Snarum, Sweden, at Bolton, Roxbury, and Littleton, Mass., and elsewhere. *Titanolivine* occurs in talcose schist at Pfunders, Tyrol, and near Zermatt, Switzerland. *Monticellite* occurs sparingly in ejected blocks of metamorphosed limestone at Mte. Somma, and in zones of contact metamorphism at Mte. Monzoni in the Tyrol, and at Magnet Cove, Ark. *Tephroite* is found in calcite at Sterling Hill and at Franklin Furnace, N. J., with zincite, franklinite, willemite; also at Pajsberg and other localities in Sweden with rhodonite and other manganese minerals.

Resemblances.—Olivine when anhedral and unaltered resembles anhedral diopside in refraction and double refraction, but differs from it in the size of the angle between the optic axes and in the position of the cleavage with respect to the optical orientation or symmetry of the crystal, the cleavage being pinacoidal in olivine and prismatic in pyroxene.

Laboratory Production.—Olivine has been obtained from the fusion of magnesian-iron silicate, corresponding in composition to basalt and similar magmas, by Fouqué and Michel-Lévy, and in those corresponding to meteorites by Daubrée. Olivine, fayalite, and other members of the series have been obtained by Berthier from the fusion of the proper constituents; also in the presence of magnesium chloride or other chlorides. These minerals are common in many furnace slags, in which they have been especially studied by Vogt.

HUMITE GROUP.

Humite, $Mg_5[Mg(F\cdot OH)]_2(SiO_4)_3$.
Chondrodite, $Mg_3[Mg(F\cdot OH)]_2(SiO_4)_2$.
Clinohumite, $Mg_7[Mg(F\cdot OH)]_2(SiO_4)_4$.

Chemical Composition.—Fluosilicates of magnesium, the proportions being nearly the same in all three minerals. A variety of humite from the Allalin region contains beryllium and titanium.

Alteration.—The minerals of this group frequently alter to serpentine and sometimes brucite.

Humite: orthorhombic, $a:b:c=0.92575:1:4.07639$ (Scacchi) or $1.0802:1:4.40334$.

Chondrodite: monoclinic, $a:b:c=1.0863:1:3.1447$ (E. S. Dana), $\beta=90°$.

Clinohumite: monoclinic, $a:b:c=1.0803:1:5.6588$ (Rath), $\beta=90°$.

Euhedral crystals of *humite* rare, small, and highly modified. Anhedral crystals in rocks often rounded or ellipsoidal, elongated parallel to the c axis or to the a axis. *Twinning* plane (017) with the two c axes at 60° 26′; also (037) with the c axes at 59° 34½′. Usually penetration twins or lamellar polysynthetic twins; sometimes trillings.

Euhedral crystals of *chondrodite* and *clinohumite* varied in habit and often highly modified, not observed in rock sections. Anhedral crystals quite irreguarly shaped, rounded or ellipsoidal as in humite. *Twinning* plane in *chondrodite* (105), less often (305); in *clinohumite* (103), less often ($\bar{1}03$). These are sometimes crossed twins, also lamellar, and are combined with polysynthetic lamellar twinning parallel to (001).

Cleavage parallel to (001) distinct in humite, somewhat so in chondrodite and clinohumite. Fracture subconchoidal to uneven. H. = 6–6.5. Sp. gr. = 3.1–3.2.

Optical Properties.—Optically positive (+). Plane of the optic axes in *humite* parallel to (001); acute bisectrix Z normal to (100); $X \parallel b$, $Y \parallel c$, $Z \parallel a$, Fig. 1. In *chondrodite* and *clinohumite* (Fig. 2) the plane of the optic axes is normal to (010), with the acute bisectrix Z also normal to (010). The obtuse bisectrix X is inclined to c, giving $X \wedge c$ in chondrodite +25° 52′, Brewster, E. S. Dana; +28° 56′, Kafveltorp, Sjögren; +30° approx., Mte. Somma, Des Cloizeaux; $X \wedge c$ in clinohumite +11°, Des Cloizeaux; +12° 28′, Mte. Somma, Klein; +7½° approx., Brewster, E. S. Dana. That

is, the angle of extinction measured from the trace of the cleavage (001) is 26°–30° in chondrodite, and $7\frac{1}{2}°$–$12\frac{1}{2}°$ in clinohumite.

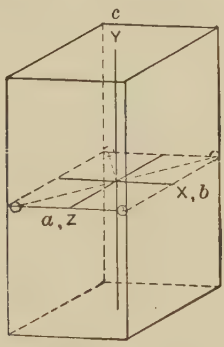


FIG. 1.

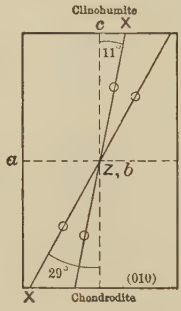


FIG. 2.

Axial angle large; dispersion weak, crossed in chondrodite and clinohumite, $\rho > v$; in yellow chondrodite from Sweden, $\rho < v$.

	$2V_r$	$2V_y$	$2V_{gr}$	
Humite, Nordmarken	68° 1′	67° 54′	67° 44′	Sjögren
Chondrodite, "	79° 40′	79° 40′	79° 38′	"
Clinohumite, "	76° 29′	76° 27′	76° 24′	"

Refraction moderate, double refraction strong.

	α	β	γ	$\gamma - \alpha$	
Humite	—	1.643	—	0.032–0.028	Lévy-Lacroix
Chondrodite, Kafveltorp	1.607	1.619	1.639	0.032	"
" Nordmarken	—	1.659	—	—	Sjögren
" "	—	1.638	—	—	Brugnatelli
Clinohumite, "	—	1.670	—	—	—

Color.—Much the same in all three minerals: colorless, white, yellow in various tints, chestnut-brown in all; deep garnet-red, brownish red, hyacinth-red, in chondrodite and clinohumite. In thin section colorless to lighter shades of the colors named. Pleochroism somewhat distinct, especially in the brown varieties. The absorption is $X > Y \geqslant Z$.

Humite — X golden yellow $Y = Z$ pale yellowish to colorless

Chondrodite and clinohumite — X honey-, golden, or brownish yellow, $Y = Z$ nearly colorless, yellowish white to yellowish green

Luster vitreous to resinous.

Occurrence.—The minerals of this group are developed chiefly in metamorphosed limestones, altered by contact with igneous rocks, such as the inclusions in Vesuvian lava, and in zones of contact meta-

morphism. Of the three minerals, clinohumite is rather rare, the others quite common. They also occur in crystalline limestones and dolomites within the crystalline schists. They are all found in ejected blocks of limestone at Vesuvius. *Humite* is found with magnetite in limestone near Filipstad, Sweden, and similarly at the Tilly Foster mines, Brewster, N. Y. *Chondrodite* occurs in limestone at Pargas and elsewhere in Finland, and with humite at the Tilly Foster mines, New York. *Clinohumite* has been found in limestone in Andalusia, Llanos de Juanar, in parallel growth with humite; in limestone near Lake Baikal, and elsewhere. Numerous similar occurrences have been noted, usually as chondrodite without specific identification. The minerals generally associated with them are phlogopite, spinel, pyroxene, also olivine and magnetite; and serpentine and sometimes brucite as alteration-products.

Resemblances.—The minerals of this group are most like olivine in refraction and double refraction, and in their manner of altering to serpentine. Humite differs from it in having a smaller angle between the optic axes and in frequently exhibiting lamellar twinning, seldom observed in olivine. Chondrodite and clinohumite differ from olivine in being monoclinic, with inclined extinction, and in frequent lamellar twinning. Humite, chondrodite, and clinohumite are distinguished from one another by the extinction angle measured from the basal cleavage.

MELILITE.

$$(Ca,Mg,Fe)_3((Al,Fe)O)_2SiO_4$$
with $(Ca,Mg)_4Si_3O_{10}$ (?)

Chemical composition uncertain, owing to varying analyses. Vogt has suggested the above formula, representing isomorphous mixtures of gehlenite and akermanite molecules.

	Sp. gr.	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O
Capo di Bove	2.95	39.27	6.42	10.17	—	6.44	32.47	1.95	1.46	—
										= 98.18
Hochbohl	2.99	44.76	7.90	5.16	1.39	8.60	27.47	2.65	0.33	1.42
										= 99.68
Mte. Somma	2.945	41.09	10.93	3.40	—	5.87	34.78	3.40	0.68	0.24
										= 100.39

Alteration.—Decomposed by hydrochloric acid with gelatinization. According to Rosenbusch, melilite alters to a fibrous mineral with rather high double refraction, which is probably a zeolite.

The fibers proceed from the basal plane (001) perpendicularly, but are sometimes divergent. Törnebohm has noted the alteration of melilite to garnet in alnöite at Alnö.

Tetragonal; $c = 0.45483$.

Euhedral crystals are usually short square prisms with $a(100)$, sometimes $m(110)$, and $c(001)$, also $r(111)$, and less often other forms, $h(310)$, Fig. 1. Also tabular parallel to (001), and anhedral grains. The usual form in rocks is that of thin tabular crystals with eight-sided or rounded outline, yielding long rectangular or lath-shaped sections

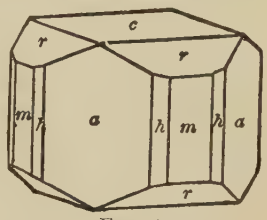


FIG. 1.

Twinning.—Cruciform twins with the vertical axes only slightly inclined, or nearly at right angles.

Cleavage parallel to (001) distinct; parallel to (100) indistinct. Fracture conchoidal to uneven. H. = 5. Sp. gr. = 2.9–3.1.

Optical Properties.—Optically negative (−), also positive (+), owing to very weak double refraction; moderately high refraction.

Humboldtilite, Vesuvius	$\omega_r = 1.6312$	$\varepsilon_r = 1.6262$	$\omega_r - \varepsilon_r = 0.0050$	Henniges
" "	$\omega_y = 1.6339$	$\varepsilon_y = 1.6291$	$\omega_y - \varepsilon_y = 0.0048$	"

According to Wülfing, $\omega_r - \varepsilon_r = 0.00530$, $\omega_y - \varepsilon_y = 0.00517$, $\omega_{gr} - \varepsilon_{gr} = 0.00521$, from which it is seen that the double refraction is least for yellow light and increases toward both ends of the spectrum.

In some crystals both positive and negative characters appear in different parts, which are sometimes arranged concentrically in zones, with isotropic portions between. Owing to the variableness in optical character and the fact that the crystal may be isotropic to one kind of light, the interference color in thin sections is often abnormal, commonly a deep purplish blue or indigo-blue.

Color.—White or pale yellow, honey-yellow, greenish yellow, reddish brown, brown. In thin section yellowish to colorless, sometimes yellow or brown. The strongly colored crystals are pleochroic; *O* light yellow, *E* dark yellow (Stelzner).

Inclusions.—Melilite, besides including occasional crystals of the minerals associated with it, very frequently contains abundant rod-like or fibrous bodies of somewhat variable shapes, occasionally terminating in knobs and suggesting the form of pegs. These inclusions all lie parallel to the *c* axis, normal to the basal plane (001). They appear to lie with the points of the rods or pegs at the surface of the crystal and the knobs toward the middle of it. This

arrangement of inclusions has been called peg ("Pflock") structure by Stelzner. The mineralogical character of the inclusions is not known, but may be glass, as they are isotropic with an index of refraction somewhat lower than that of melilite. They have also been considered as of secondary origin by Gentil, possibly a zeolite.

Occurrence.—Melilite occurs in non-feldspathic basic igneous rocks low in silica, chiefly in extrusive or lava forms, and in a few intrusive rocks of the same composition, as in alnöite. It is not of common occurrence, and is found in melilite-basalt of Hochbohl in Württemberg, of the Swabian Alb, of Görlitz, and of Cape Colony; also in some nephelite- and leucite-basalts; in leucitophyre at Capo di Bove, near Rome; in nephelite-basalt of the Hegau; on Oahu, Hawaiian Islands; in Uvalde County, Texas, and elsewhere. Humboldtilite occurs in blocks of altered limestone inclosed in Vesuvian lava on Mte. Somma.

Resemblances.—Melilite is somewhat like zoisite and vesuvianite in double refraction, but has lower refraction and different crystal habit. It also behaves differently toward acids. It resembles gehlenite in refraction, but has lower double refraction. It is like fuggerite in double refraction, but has lower refraction.

Laboratory Production.—Melilite has been obtained by Fouqué and Lévy by fusing together its constituents; also by Bourgeois, who obtained melilite of different compositions by varying the amount of Ca, Mg, Fe, and by introducing Mn. He observed that the presence of sodium facilitated the crystallization. Melilite is a common mineral in furnace slags accompanying olivine, and has been specially studied by Vogt, who observed that the order of crystallization of melilite and olivine depends upon the relative proportion of Ca and Mg in the flux, that is, on the saturation of the solution. Melilite also is formed in the manufacture of Portland cement.

AKERMANITE.

$R_4Si_3O_{10}$.

$4RO \cdot 3SiO_2$, in which R is chiefly Ca; also Mg, Mn, Fe. Akermanite is a compound crystallizing from furnace slags and isomorphous with melilite. It is tetragonal in tabular crystals, with cleavage parallel to (110) and perhaps also to (001). It is optically positive (+). It seems to form one extreme of an isomorphous series including melilite and gehlenite, both of which occur similarly in furnace slags. Gehlenite is optically negative, while melilite is near the middle of the series and is variably positive and negative.

GEHLENITE.

$Ca_3Al_2Si_2O_{10}$.

$3CaO \cdot Al_2O_3 \cdot 2SiO_2 = SiO_2$ 30.9, Al_2O_3 26.2, CaO 42.9 = 100. Some MgO and Fe_2O_3 are generally present. It gelatinizes with hydrochloric acid. At Monzoni it has been altered in some instances to fassaite, in others to grossularite.

Tetragonal; $c = 0.40006$.

Euhedral crystals with $c(001)$, $a(100)$, $r(111)$, and other faces subordinate, Fig. 1. Usually short square prisms, sometimes tabular, often resembling a cube; also anhedral grains.

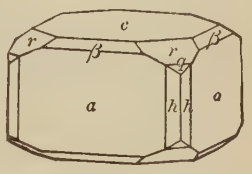


FIG. 1.

Cleavage parallel to (001) imperfect; (100) in traces. Fracture uneven to splintery. H. = 5.5–6. Sp. gr. = 2.9–3.07.

Optical Properties.—Optically negative (−). Refraction moderate, double refraction weak.

$\omega = 1.663$, $\varepsilon = 1.658$, $\omega - \varepsilon = 0.005$, Lévy–Lacroix.
$\omega_y - \varepsilon_y = 0.00618$, Wülfing.

Color.—Different shades of grayish green to liver-brown. In thin section colorless. Luster resinous to vitreous.

Occurrence.—Gehlenite occurs as a secondary mineral produced by contact metamorphism in limestone, as at Monzoni, Fassathal; also in the Fleimsthal, and at Oravitza in the Banat, inclosing vesuvianite. It occurs on the Kaiserstuhl along the contact of haüynophyre and limestone.

Resemblances.—Gehlenite is similar to melilite and vesuvianite. It differs from melilite in the interference color. It has lower refraction than vesuvianite. It has similar optical properties to those of apatite, but differs from it in crystal system.

Fuggerite appears to be a variety of gehlenite occurring in the contact zone at Monzoni. It has almost the same chemical composition, crystal habit, cleavage, and optical properties as gehlenite. The refraction is slightly higher. $\omega_y - \varepsilon_y = 1.691$. Isotropic for yellow light, weakly doubly refracting for others.

Laboratory Production.—Gehlenite has been obtained by Bourgeois by fusion of the constituents. It is crystallized in furnace slags at Oldbury, England, and Holzhausen, Hesse; also at McVille, Armstrong, Pa.

VESUVIANITE.

$Ca_6(AlOH)Al_2(SiO_4)_5$.

Chemical Composition.—A basic calcium-aluminium silicate of variable composition and uncertain formula. Magnesium and manganese are often present, and alkalies in small quantities; ferric iron may replace aluminium. Titanium, fluorine, and boron are also sometimes present.

Alteration.—Partially decomposed by hydrochloric acid. Alteration has not been observed in vesuvianite in rock sections, but it is known to alter to clinochlore, mica, diopside, and garnet.

Tetragonal; $c=0.537195$.

Euhedral crystals commonly short prisms with $m(110)$ and $a(100)$, $c(001)$ and $p(111)$, and other forms, less often bipyramidal (Figs. 1, 2, and 3). Anhedral crystals irregular, or in aggregates of parallel or divergent prisms; also granular.

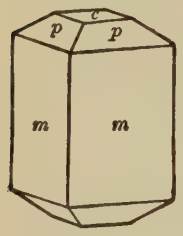


Fig. 1.

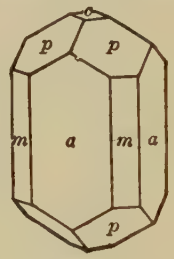


Fig. 2.

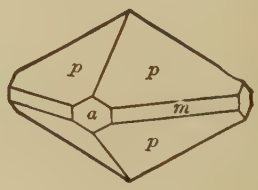


Fig. 3.

Cleavage parallel to (110) not very distinct; (100) and (001) still less so. Sometimes lamellar parallel to (001). Fracture subconchoidal to uneven. H.=6.5. Sp. gr.=3.35–3.45.

Optical Properties.—Optically negative (−), rarely positive (+), viluite; variably negative and positive for different kinds of light in crystals from Fassathal and Fleimsthal. In some crystals optically biaxial. Refraction high, double refraction weak.

	ω_Y	ε_Y	$\omega-\varepsilon$	
Ala, green	1.719–1.722	1.718–1.720	—	Des Cloizeaux
" —	1.7235	1.7226	0.0009	Osann
" brown	1.732	1.726	0.006	Hlawatsch
Poljakowsk, light green	1.7120	1.7108	0.0012	"
Sandford, Me., green-brown	1.705	1.701	0.004	"
			$\varepsilon-\omega$	
Sforzella, Predazzo, brown	1.716	1.717	0.001	"
Vilui, —	1.716	1.721	0.005	"

ANALYSES OF VESUVIANITE.

	Sp. gr.	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	CaO	MgO	Na_2O	$\frac{K_2O}{Li_2O}$	H_2O	F	
Vesuvius, brown	3.448	36.98	—	16.70	2.99	2.01	0.57	35.67	2.62	0.43	0.08	1.32	1.08	=100.45
Vilui, —	3.331	38.30	1.09	13.07	4.25		tr.	35.92	5.83	0.37		0.96		= 99.79
Gleinitz, colorless	—	37.57	—	16.30	1.82	2.76	—	36.26	1.75	und.	—	3.01	—	= 99.47
Jordansmühl, —	—	37.51	—	21.24	0.69	—	—	35.45	2.11	—	—	2.77	—	= 99.77
Monzoni, yellow-brown	3.413	37.50	0.28	16.23	3.76	0.33	—	36.31	3.13	tr.	—	2.14	—	= 99.68
Ala, green	3.427	37.36	0.18	16.30	4.02	0.39	—	36.65	3.02	tr.	—	2.89	—	=100.81
Tellemarken, blue	—	37.90	0.26	19.47	0.40	0.21	0.91	36.06	2.17	0.14	0.11	0.67	1.72	$\frac{CuO}{0.73}$=100.75
San Carlos, Cal., —	3.445	36.56	—	17.04	5.93	—	0.18	35.94	1.07	—	0.51	2.00	—	= 99.23
Sandford, Me., brown	3.419	37.49	—	16.03	2.79	3.08	0.37	33.84	2.13	1.83	0.16	1.25	1.92	=100.89

Vesuvianite, in crystals that are sometimes uniform in color, in other cases differently colored in zones, often exhibits anomalies between crossed nicols, which consist in differences of interference colors in bands or spots, accompanied by variation in the positive and negative character. The differences in interference colors are due to the fact that the crystal in different places is isotropic for certain light waves, because of the variableness in the velocities of transmission of different kinds of light. Such light-waves are then extinguished, and the resulting interference colors differ accordingly.

Other crystals of vesuvianite exhibit anomalous biaxial phenomena, the value of $2E_y$ reaching 62° 47′ in crystals from Ala. Such crystals are usually made up of segments with different optical behavior, which are oriented with respect to the outward form of the crystal, as in the case of garnet, analcite, and some other minerals. The phenomena appear to be the result of molecular strain subsequent to crystallization.

Color.—Brown to green, occasionally sulphur-yellow or pale blue and rose-red. In thin section colorless to lighter shades of the colors mentioned. Pleochroism weak and only noticeable in thin sections when the crystal is strongly colored. In thicker plates the following pleochroism has been observed:

	O	*E*	
Ala, green	greenish yellow	grass-green	Des Cloizeaux
Gleinitz, greenish	colorless	light golden yellow	von Lasaulx
Poljakowsk, clear green	yellow	light flesh-gray	Hlawatsch
Tellemarken, blue	dark blue	nearly colorless	Des Cloizeaux
Ala, brown	yellow-brown	lighter with yellow tinge	Hlawatsch
Sforzella, brown	brownish gray	yellow-green	"
Jordansmühl, peach-blow-red	colorless	rose-red	von Lasaulx
Gleinitz, rose-red	colorless	light rose-red	"
" amethyst-color	light gray	peachblow-red	"

Occurrence.—Vesuvianite is chiefly developed in metamorphosed limestones by contact metamorphism, or in blocks of limestone inclosed in igneous rock, as at Vesuvius. As a product of contact metamorphism it is found at Monzoni in the Fassathal; in the Ala valley, Piedmont, and elsewhere in Europe; at Morelos, Mexico, and in numerous localities in the United States and Canada. In these occurrences it is usually accompanied by garnet, diopside, wollastonite, epidote, and other minerals. It occurs less commonly in gneiss and other crystalline schists, as in the calcite-diopside-schist

at Tschammendorf, Silesia, and in amphibolite at Klopfberg, Lower Austria.

Resemblances.—Vesuvianite in rock sections is most like zoisite and gehlenite (fuggerite), and is somewhat like andalusite. It differs from zoisite in the absence of cleavage; from gehlenite in having slightly higher refraction and in its behavior toward acids; from andalusite it is distinguished by the size of the angle between the optic axes.

Laboratory Production.—Vesuvianite has not yet with certainty been produced in the laboratory, though claimed by Mitscherlich, and later by Daubrée. Doelter and Hussak obtained from vesuvianite, when fused and slowly cooled, a mixture of meionite, melilite, and anorthite.

EPIDOTE GROUP.

$$\overset{II}{R}_2\overset{III}{(ROH)}\overset{III}{R}_2(SiO_4)_3.$$

$\overset{II}{R}$ = Ca, $\overset{II}{Fe}$; $\overset{III}{R}$ = Al, $\overset{III}{Fe}$, $\overset{III}{Mn}$, Ce, etc.

Orthorhombic.—Zoisite (thulite).

Monoclinic.—Epidote, piedmontite, allanite.

Zoisite and epidote are similar in composition and in crystal forms, hardness, and specific gravity, and, though orthorhombic and monoclinic, are classed together in the same manner as the orthorhombic and monoclinic pyroxenes and amphiboles.

ZOISITE.

$$Ca_2(AlOH)Al_2(SiO_4)_3.$$

Basic orthosilicate, $4CaO \cdot 3Al_2O_3 \cdot 6SiO_2 \cdot H_2O = SiO_2$ 39.7, Al_2O_3 33.7, CaO 24.6, H_2O 2.0 = 100. The aluminium is sometimes replaced by iron, up to 4 per cent. of Fe_2O_3, grading into epidote. It may also contain some manganese (thulite). Not decomposed by acids.

Orthorhombic; $a:b:c = 0.61963:1:0.34295$.

Euhedral crystals prismatic parallel to the c axis; striated or furrowed parallel to this axis. Forms present commonly (100), (010), (110), (120), and other prismatic faces of this order. Terminal planes less frequently developed, (101), (011), (111), and other bipyramids. Crystals in rocks usually subhedral or anhedral; prismatic, or tabular parallel to (010); in parallel or divergent aggregates, sometimes irregularly shaped anhedrons.

Cleavage perfect parallel to (010); sometimes developed parallel to (100) in very thin sections. Fracture uneven to subconchoidal. H. = 6–6.5. Sp. gr. = 3.25–3.37.

Optical Properties.—Optically positive (+); acute bisectrix Z is normal to (100), but the plane of the optic axes is not always in the same position even in one crystal. It is usually parallel to (010), so that $X \parallel c$, $Y \parallel b$, $Z \parallel a$; but in parts of one crystal or throughout the whole of some crystals it is parallel to (001), $X \parallel b$, $Y \parallel c$, $Z \parallel a$ (Fig. 1). The axial angle $2V$ varies from 0° to 60°, sometimes in one crystal, and is larger in crystals with the plane of the optic axes parallel to (001). The dispersion is strong, $\rho < v$ in crystals of the first kind, $\rho > v$ in those of the second.

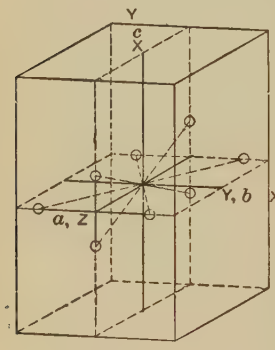


Fig. 1.

Refraction high, double refraction low, but the interference color on sections parallel or nearly parallel to (100) in zoisite with small optic angle is indigo-blue, as in epidote and melilite, though generally not so intense as in melilite. It is due to the same cause, namely, the strong dispersion of the optic axes and the much wider angle for blue than for red.

	α_Y	β_Y	γ_Y	$\gamma - \alpha$	
Zoisite, Saualpe	1.696	1.696	1.702	0.006	Lévy-Lacroix
" Cottische Alps	1.6961	1.6961	1.7034	0.0073	Wallérant
" Gorner glacier	1.6973	1.7002	1.7061	0.0088	Weinschenk
" Tyrol	1.700	1.700	1.705	0.005	Zimanyi
" Ducktown, Tenn.	1.7002	1.7025	1.7058	0.0056	Osann

Color.—Grayish white, gray, yellowish brown, greenish gray, apple-green; peach-blossom red to rose-red (thulite). In thin section colorless, except thulite, which is pleochroic in thin sections. In thicker plates or crystals zoisite is pleochroic.

Zoisite, Gorner glacier	$X = Z$ bluish green	Y light wine-yellow	Weinschenk
" Prägraten	$X = Z$ bluish green	Y light orange	"
Thulite	X light rose to colorless	Y deep rose Z yellow	Lacroix

Occurrence.—*Zoisite* occurs in some crystalline schists, especially in eclogite, amphibolite, and glaucophane-schist on Syra, and in the Coast Ranges of California. It frequently carries inclusions of amphibole microlites. It occurs as an alteration-product in metamorphosed gabbros and related rocks, accompanying epidote,

with which it is sometimes intergrown in parallel orientation, (010) of zoisite parallel to (100) of epidote, and the prismatic axes of both minerals parallel. This is the position, as pointed out by Tschermak, in which the similarity of the crystal forms becomes apparent, showing the approach to isomorphism. Zoisite is a chief constituent of saussurite, an alteration-product of lime-soda-feldspars in gabbros.

Thulite occurs with vesuvianite, garnet, epidote, and fluorite at Kleppau in Tellemarken, Norway; also near Arendal. It forms small veins with talc and actinolite in granite at Traversella, Piedmont. With withamite it gives the red color to *porfido rosso antico*, according to Rosenbusch.

Resemblances.—Zoisite resembles colorless epidote in habit, refraction, and double refraction. It differs from it in having a smaller angle between the optic axes and in being optically positive. In some zoisites the plane of the optic axes is parallel to the plane of cleavage. Zoisite is somewhat like melilite in double refraction, but has higher refraction and better cleavage. It resembles colorless vesuvianite in refraction and double refraction, but differs from it in cleavage, and in biaxial characters in most cases.

MONOCLINIC EPIDOTES.

Epidote,	$Ca_2(AlOH)(Al,Fe)_2(SiO_4)_3$.
Piedmontite,	$Ca_2(AlOH)(Al,Mn,Fe)_2(SiO_4)_3$.
Allanite,	$(Ca,Fe)_2(AlOH)(Al,Ce,Fe)_2(SiO_4)_3$.

Chemical Composition.—Basic orthosilicates of calcium and aluminium with iron in variable amounts in epidote; iron and manganese in piedmontite; and iron and the cerium metals in allanite. In epidote the proportions of aluminium to iron vary from 6:1 to 3·2. Varieties with little iron have been called clinozoisite. In piedmontite the proportions of aluminium, iron, and manganese vary as shown in the analyses cited. In allanite, in addition to variable amounts of cerium, didymium, and lanthanum, there may be smaller amounts of the yttrium group of metals.

Alteration.—Epidote is partially decomposed by hydrochloric acid; piedmontite is not decomposed by it; allanite in most varieties gelatinizes with hydrochloric acid. Epidote in rock sections does not appear to have undergone alteration in any case. Allanite becomes hydrated, losing color. Epidote may be altered by metamorphism to vesuvianite, garnet, and clinochlore.

ANALYSES OF MONOCLINIC EPIDOTES.

	Sp. gr.	SiO_2	ThO_2	Al_2O_3	Fe_2O_3	Ce_2O_3	Di_2O_3	La_2O_3	Y_2O_3	Er_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	H_2O
Epidote, Untersulzbach	3.446	37.83	—	23.43	13.31	—	—	—	—	—	0.48	tr.	tr.	23.47	—	—	2.06
																	=100.58
" Zillerthal	—	38.46	—	28.59	5.76	—	—	—	—	—	0.53	—	—	24.60	—	—	1.92
																insol.	0.42=100.28
" Syra	—	38.15	—	25.30	9.30	—	—	—	—	—	—	—	0.24	25.10	—	—	1.80
																	= 99.89
Withamite straw-yellow } Glencoe }	—	43.23	—	23.09	6.68	—	—	—	—	—	1.13	0.14	0.88	20.00	0.94	0.96	2.40
																Li_2O 0.25, insol.	0.35= 99.70
Epidote Macon Co., N C.	3.269	36.95	—	25.82	9.97	—	—	—	—	—	1.34	0.56	0.56	21.86	—	—	3.02
																	=100.08
Piedmontite. St. Marcel	3.518	38.64	—	15.03	8.38	—	—	—	—	—	—	Mn_2O_3 15.00	—	22.19	—	—	1.78
																	=101.02
" Japan	—	36.16	—	22.52	9.33	—	—	—	—	—	—	6.43	0.40	22.05	0.44	—	3.20
																	=100.53
" Jakobsberg	—	36.44	—	24.65	12.44	—	—	—	—	—	—	4.52	—	19 52	—	—	3.19
																	=100.76
Allanite, Hitterö	3.52	31.63	0.87	13.21	8.39	8.67	5.60	5.46	0.87	0.52	7.86	1.66	0.08	10.48	—	0.28	3.49
																	= 99.07
" Näskilen	3.33	32.01	1.14	17.54	5.20	6.21	10.78	0.24	1.38	1.53	9.92	0.47	—	12.03	—	0.15	1.79
																	=100.39
" Amelia Co., Va.	3.323	32.35	—	16.42	4.49	11.14	6.91	3.47	—	—	10.48	1.12	—	11.47	0.46		2.31
																	=100.62
" Balsam Gap, N.C.	3.400	32.79	—	18.16	1.64	6.07	14.40	—	1.84	—	10.08	1.23	0.15	10.95	0.33	0.12	1.89
																	= 99.65
" Douglas Co., Colo.	3.52	31.13	0.21	11.44	6.24	12.50	10.98		—	—	13.59	0.61	0.16	9.44	0.56	tr.	2.78
																BeO	0.27= 99.91

Monoclinic.—Epidote, $a:b:c = 1.5787:1:1.8036$, $\beta = 64° 37'$.
Piedmontite, " $= 1.6100:1:1.8326$, $\beta = 64° 39'$.
Allanite, " $= 1.5509:1:1.7691$, $\beta = 64° 59'$.

Euhedral crystals of epidote commonly prismatic parallel to the b axis, with $a(100)$, $c(001)$, $r(\bar{1}01)$, and other pinacoids in this zone, besides $n(\bar{1}11)$, $m(110)$, $o(011)$, commonly, and numerous other forms less frequently as terminal planes (Figs. 1 and 2). The cross-section with angles of 115° 23′ and 116° 18′ (Fig. 3) is character-

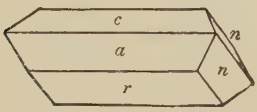


Fig. 1.

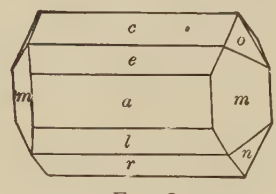


Fig. 2.

istic of minerals of this group. Crystals rarely elongated parallel to the c axis, oftener in allanite, which is sometimes flattened parallel to $a(100)$. Habit of all minerals of this group similar, but euhedral crystals of piedmontite and allanite are rare. Subhedral and anhedral crystals common in rocks, prismatic, divergent or parallel; often in irregularly shaped anhedrons and granular aggregations.

Twinning and composition plane $a(100)$, sometimes lamellar; rarely a twinning parallel to $c(001)$.

Cleavage parallel to (001) perfect in epidote and piedmontite, distinct in fresh allanite; parallel to (100) imperfect in all three

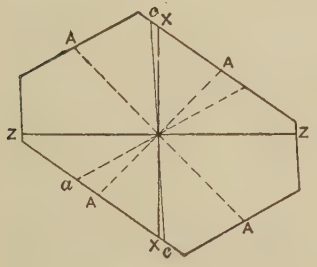


Fig. 3.

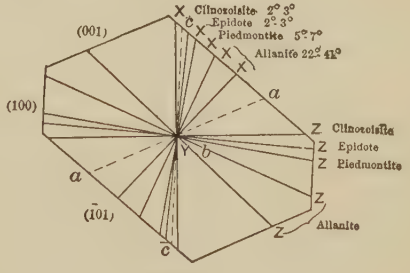


Fig. 4.

minerals. Fracture uneven. H.=6–7, epidote; 6.5, piedmontite; 5.5–6, allanite. Sp.gr.=3.25–3.5, epidote; 3.404, piedmontite; 3.5–4.2, allanite.

Optical Properties.—Plane of the optic axes parallel to (010), perpendicular to the basal cleavage. In clinozoisite the bisectrix X is inclined 2°–3° to the crystal axis c in the obtuse angle β, and the same amount in the acute angle β for epidote. The bisectrix Z is almost normal to (100), Fig. 4. In piedmontite the inclination of X to c is 5°–7° in the acute angle β, and the bisectrices are noticeably dispersed; dispersion inclined. In allanite the bisectrix X is inclined 22°–41° to c in the acute angle β. In that from Grefsenaas, Norway, the plane of the optic axes is perpendicular to (010) (Brögger).

	$X_r \wedge c$	$X_y \wedge c$	$X_{gr} \wedge c$		
Clinozoisite, Simplon	1° 58′	2° 28′	3° 2′	$\rho < v$	Preiswerk
" Huntington, Mass.	1° 51′	2° 9′	2° 12′	$\rho < v$	Forbes
Epidote, Knappenwand	2° 56′	—	2° 26′	$\rho > v$	Klein
Piedmontite, Jakobsberg	4° 34′	—	5° 20′	$\rho < v$	Flink
" St. Marcel	7° 26′	6° 41′	—	$\rho > v$	Laspeyres

	$X \wedge c$	
Allanite, Arendal and Hitterö	22°–41°	Brögger
" Grefsenaas, Norway	28° 30′–37° 30′	"
" —	36° approx.	Rosenbusch
" Gyttorp, Sweden	46°–47°	Törnebohm

The angle between the optic axes is large and varies with the chemical composition, together with the indices of refraction and the double refraction. The angle $2V$ about Z increases with the percentage of iron from clinozoisite to epidote.

	Fe_2O_3	$2V_y^x$	$2V_y^x$	Opt.	$\gamma - \alpha$
Clinozoisite, Prägraten	2	81° 40′	98° 20′	+	0.0056
" Rothenkopf	4	89° 16′	90° 34′	+	0.0105
" Huntington	6.2	89° 28′	90° 32′	+	0.010
Epidote, Zillerthal	7.9	92° 14′	87° 46′	−	0.0144
" Knappenwand	16	106° 21′	73° 39′	−	0.0372

For piedmontite from Jakobsberg, with 4.52 Mn_2O_3, which is optically negative, $2V_r^x = 88° 44′$ (Flink), and increases with the percentage of manganese, the more manganesian varieties being optically positive, $2V^x > 90°$.

The optical character of allanite is uncertain, that from Grefsenaas, Norway, being probably negative (−); that from Arendal is optically positive (+).

Refraction high; double refraction variable, from low in clinozoisite to high in epidote richer in iron; high also in piedmontite and allanite, when fresh, similar to that of epidote. Double refrac-

tion in allanite ranges to 0° with alteration. It is stronger in crystals in recent volcanic rocks than in those in granites and gneiss.

Clinozoisite, Prägraten	$\alpha = 1.7176$	$\beta = 1.7195$	$\gamma = 1.7232$	$\gamma - \alpha = 0.0056$	Weinschenk
" Rothenkopf	$= 1.7238$	$= 1.7291$	$= 1.7343$	$= 0.0105$	Weinschenk
" Huntington	$\alpha_y = 1.714$	$\beta_y = 1.716$	$\gamma_y = 1.724$	$= 0.010$	Forbes
Epidote, Zillerthal	$= 1.7238$	$= 1.7291$	$= 1.7343$	$= 0.0144$	Weinschenk
" Knappenwand	$\alpha_r = 1.7305$	$\beta_r = 1.7540$	$\gamma_r = 1.7677$	$= 0.0372$	Klein
" Traversella	—	—	—	$= 0.061$	Ramsay
Withamite, Glencoe	—	—	—	$= 0.05$	Lacroix
Piedmontite, —	similar to those of epidote				
Allanite, Näskilen, Norway	—	$\beta = 1.682$	—	—	Lévy-Lacroix
" Edenville	$\alpha > 1.78$	—	—	—	Lévy-Lacroix
" —	—	—	—	$= 0.032$	Lévy-Lacroix

Color.—In *clinozoisite* rarely colorless, gray and grayish white, greenish grading into the colors of *epidote*, which are pistachio-green or yellowish green, brownish green, greenish black, and black; in the variety *withamite* clear red and yellow; in *piedmontite* reddish brown or reddish black; in *allanite* pitch-brown to black, brownish, greenish, grayish, or yellowish. In thin sections colorless to colored with marked pleochroism. In *clinozoisite* and *epidote* colorless to faintly greenish yellow, sometimes noticeably pleochroic between colorless and green-yellow; in thicker plates strongly pleochroic. In *piedmontite* the pleochroism is pronounced and characteristic. In *allanite* double-refracting crystals are distinctly pleochroic.

The directions of maximum absorption for different colors do not coincide with the bisectrices in epidote, but are strongly dispersed in the plane of symmetry (010).

Occurrence.—*Clinozoisite* and *epidote* occur abundantly as secondary minerals in igneous rocks, resulting from the alteration of ferromagnesium minerals and also of lime-soda-feldspars. They commonly accompany chlorite. In the same manner they occur as secondary minerals in the crystalline schists. *Epidote* is in some cases pyrogenetic in igneous rocks, occurring in euhedral crystals in granite from Ilchester, Md., and elsewhere. It is occasionally inter-

Pleochroism: Clinozoisite and Epidote.

		X	*Y*	*Z*	
Huntington	(gray)	nearly colorless with lavender-blue tint	lavender-blue	colorless with green tint	Forbes
Zillerthal	(greenish)	colorless	plum-blue	colorless	"
"	(reddish)	pale green	plum-blue	pale rose	
Rothenkopf	(green)	pale lemon-yellow	yellowish green with blue-violet tint	bright rose	Weinschenk
"	(reddish)	lemon-yellow to green	yellowish green with blue-violet tint	light wine-yellow	
Avigliana		very pale yellow	light greenish yellow	yellowish green	Boeris
Knappenwand		yellow	brown	green	Klein
Glencoe (*Withamite*)		lemon-yellow	light rose	bright rose	Lacroix

Piedmontite.

Ile de Groix	yellow	light rose	bright rose	Lacroix
" " "	yellow	light rose	carmine	Rosenbusch
South Mountain, Pa.	yellow to orange	amethystine	carmine	G. H. Williams
Jacobsberg	orange	violet	carmine	Flink
St. Marcel	orange	dark amethystine	dark garnet-red	Laspeyres

Allanite.

Gyttorp	light greenish gray	green brown-red	brown-green	Törnebohm
Pont Paul	greenish yellow	reddish brown	brown-yellow	Lévy-Lacroix
Hiei Japan	greenish brown	reddish brown	brownish yellow	Hiki
Valsavaranche	light yellow-brown	bright reddish brown	sepia-brown	Novarese
Ilchester	light yellow-brown	chestnut-brown	dark gray-brown	Hobbs
Trotter Mine	yellowish brown	dark red-brown	dark grayish brown	Eakle
Suhl	brownish gray	chestnut-brown	dark chestnut-brown	Rosenbusch
Grefsenaas	dark brown	brownish yellow	deep brown-black	Brögger

grown in parallel orientation with allanite in such rocks. Epidote is common in many metamorphic rocks, especially those derived from limestones and rocks rich in calcium, both in regions of dynamic metamorphism and in zones of contact metamorphism, where it accompanies vesuvianite, garnet, pyroxene, and other minerals. *Withamite* is a variety of epidote containing 0.14 MnO, according to Heddle, occurring in porphyry at Glencoe, Argyleshire, Scotland.

Piedmontite occurs in igneous rocks as a secondary mineral in microscopic crystals or in larger radial aggregations, as in aporhyolite at South Mountain, Pa.; in the ancient *porfido rosso antico* of Egypt, and elsewhere. It is also a constituent of some crystalline schists, as in mica-schist of Ile de Groix, Brittany, and at St. Marcel, Piedmont; and in piedmontite-schist, glaucophane-schist, and other members of the crystalline schists in Japan.

Allanite occurs in nearly all kinds of igneous rocks in very small amounts, but is more frequent in granites and pegmatites. In granite it is sometimes surrounded by epidote in parallel orientation as described by Hobbs and as shown in Fig. 5. It also occurs in gneiss,

Fig. 5.

mica-schist, amphibolite, and sometimes in crystalline limestone, as at Auerbach. *Orthite* is a name in common use for allanite. The original orthite was in acicular crystals sometimes a foot long at Finbo, Sweden, often containing some water and apparently a hydrated allanite.

Resemblances.—*Epidote* is somewhat like olivine and colorless pyroxene in refraction and double refraction. It is distinguished from these minerals by its pleochroism, when present, from colorless to green-yellow; further by its cleavage and the optical orientation with respect to it.

Clinozoisite is like zoisite except for the monoclinic symmetry and the absence of the peculiar blue interference color. *Piedmontite* is sufficiently characterized by its pleochroism combined with its other properties. *Allanite* is somewhat like brown hornblende, but differs from it in the absence of cleavage and in habit and optical orientation.

FOUQUÉITE.

Chemical composition like that of zoisite with a little iron. SiO_2 38.3, Al_2O_3 31.9, FeO 4.4, CaO 23.5, ign. 2.7 = 100.8.

Monoclinic. Anhedral, in rounded elongated crystals. Sometimes in polysynthetic twins, with (100) as twinning plane.

Cleavage parallel to (001), which appears to be inclined 108° to the prismatic axis of the crystals. Sp. gr. = 3.24–3.31.

Optical Properties.—Optically positive (+). Plane of the optic axes parallel to the cleavage, (001); with the actute bisectrix Z normal to (010). Axial angle, $2V = 90°$ approx. Dispersion weak, $\rho < v$. Double refraction moderate, $\gamma - \alpha = 0.020$. Color yellow or white, very feebly pleochroic. $X = Z$ colorless, Y very pale yellow.

Fouquéite occurs in anorthite-gneiss with scapolite, garnet, amphibole, pyroxene, and epidote at Salem, and occasionally at Kandy, Ceylon. It appears to be a variety of clinozoisite.

PREHNITE.

$H_2Ca_2Al_2(SiO_4)_3$.

An acid orthosilicate of calcium and aluminium with the proportions, $H_2O \cdot 2CaO \cdot Al_2O_3 \cdot 3SiO_2 = SiO_2$ 43.7, Al_2O_3 24.8, CaO 27.1, H_2O 4.4 = 100.

Decomposed slowly with hydrochloric acid.

Orthorhombic; sphenoidal class. $a:b:c = 0.84009:1:0.55494$.

Euhedral crystals rare, usually tabular parallel to c(001) with m(110) and a(100), and prisms in the zone of the b axis subordinate (Fig. 1); sometimes prismatic with m(110), c(001), b(010), and o(061) (Fig. 2). Commonly in groups of tabular crystals, united

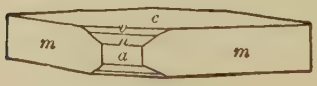


Fig. 1.

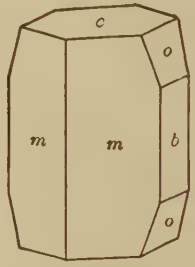


Fig. 2.

by (001), often barrel-shaped. Also globular, in prismatic, tabular or granular aggregations.

Cleavage parallel to (001) distinct. Fracture uneven. H.=6–6.5. Sp. gr.=2.80–2.95.

Optical Properties.—Optically positive (+); plane of the optic axes parallel to (010); acute bisectrix Z normal to (001), $X \parallel a$, $Y \parallel b$, $Z \parallel c$, Fig. 3. Axial angle large and variable; dispersion weak, $\rho > v$, in some cases $\rho < v$.

Dauphiné	$2E_r = 124° 54'$ to $129° 9'$		Des Cloizeaux
Pyrenees	$2E_r = 122° 59'$ to $125° 27'$		
Jordansmühl	$2E_y = 135° 26'$	$2V_y = 69° 22'$	Beutell

Refraction moderate, double refraction strong.

Ratschinges	$\alpha = 1.616$	$\beta = 1.626$	$\gamma = 1.649$	$\gamma - \alpha = 0.033$	Des Cloizeaux

In some instances prehnite exhibits optical anomalies, both as to the optical orientation, the extinction of light between crossed nicols, and as to the interference colors, which may be deep azure-

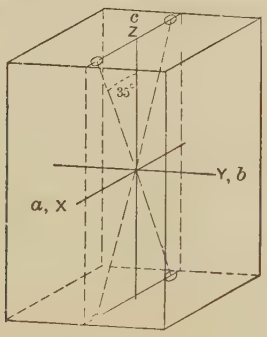


Fig. 3.

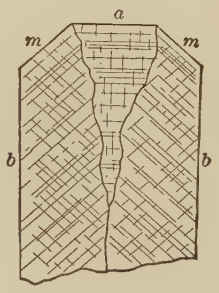


Fig. 4.

blue and leather-brown. In some sections it exhibits a microscopic lamination like that of microcline. In such crystals a section parallel to (001) shows three parts, as in (Fig. 4); a central wedge with lamellæ lying parallel and others normal to a, with parallel extinction and the plane of the optic axes in the two sets of lamellæ at right angles to one another; the optic angle being small, sometimes 0°, with crossed dispersion, the plane of the optic axes for red being at right angles to that for blue. The two outer portions consist of lamellæ, one set in each part parallel to the m face of that part, the other set almost perpendicular to this face, intersecting the first at 82°–83°. In these parts light is not completely extinguished in any position between crossed nicols. The interference figures are much distorted with marked crossed dispersion. According to E. Mallard the wedge-shaped part consists of lamellæ having in one case the acute bisectrix, in the other the obtuse bisectrix, normal to the base of

the compound individual; the outer portions consist of lamellæ oriented as though rotated on the c axis 60° to one another.

Color light green, oil-green, white, gray. In thin section colorless. Luster vitreous, on (001) weak pearly.

Occurrence.—Prehnite occurs with datolite and the zeolites in cavities in basic igneous rocks, basalt, gabbro, also in diorite and granite; and in cracks in crystalline schist. It is a constituent of some amphibolites, augite-gneisses, and wollastonite-rocks. It is sometimes found in metamorphosed limestone and dolomite.

Resemblances.—Prehnite is somewhat similar in refraction to andalusite, topaz, wollastonite, and datolite. From the first three it is distinguished by much higher double refraction; from datolite by lower double refraction.

LAWSONITE.

$H_4CaAl_2Si_2O_{10}$.

Or $CaO \cdot Al_2O_3 \cdot 2SiO_2 + 2H_2O$. Chemical analysis, SiO_2 38.10, Al_2O_3 28.88, Fe_2O_3 0.85, CaO 18.26, MgO 0.23, Na_2O 0.65, H_2O 11.42 = 98.39. Not acted on by hydrochloric acid.

Orthorhombic.—$a:b:c = 0.6652:1:0.7385$.

Euhedral crystals prismatic with $m(110)$, $b(010)$, $c(001)$, $d(011)$, and sometimes (041) Fig. 1; also tabular parallel to (001) when in the rock mass.

Twinning plane and composition plane (110).

Cleavage parallel to (010) perfect; parallel to (001) rather perfect; less so parallel to (110). H. = 8. Sp. gr. = 3.084–3.091.

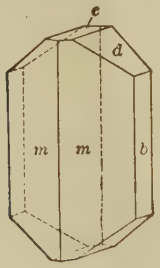


Fig. 1.

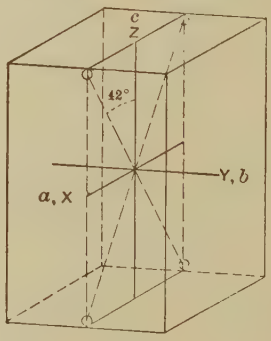


Fig. 2.

Optical Properties.—Optically positive (+); plane of the optic axes parallel to (010); acute bisectrix Z normal to (001); $X \parallel a$, $Y \parallel b$,

$Z \parallel c$. Angle between the optic axes large, $2V_y = 84° 6'$. Refraction and double refraction moderately high.

Tiburon, Cal.	$\alpha_y = 1.6650$ $\beta_y = 1.6690$	$\gamma_y = 1.6840$	$\gamma - \alpha = 0.0190$	Ransome–Palache
Monte Brancata	$\beta = 1.676$	$\gamma - \alpha = 0.020$	$2V > 80°$	Viola
	$\beta = 1.67$ approx.	$\gamma - \alpha = 0.021$		Lacroix

Color.—Colorless to gray-blue, the colors often distributed in bands parallel to the prism face as in cyanite. In thin section colorless. Pleochroic in thick plates, X blue, Y colorless with pale-yellowish tint.

Occurrence.—Lawsonite occurs with margarite, epidote, and actinolite in amphibole-schist on Tiburon Peninsula, Cal. and also is developed in metamorphosed gabbros and basalts. It has been found in a number of localities in Italy accompanying albite in saussuritized feldspar. It has also been found in Corsica and New Caledonia. Lawsonite frequently accompanies glaucophane and other blue amphiboles in schistose rocks derived from gabbro.

Resemblances.—Lawsonite is like olivine in refraction, but has lower double refraction. It resembles andalusite and zoisite in refraction, but has higher double refraction. It is somewhat like the scapolites but is biaxial.

CORDIERITE.

$$H_2(Mg,Fe)_4Al_8Si_{10}O_{37}.$$

Or $H_2O \cdot 4(Mg,Fe)O \cdot 4(Al_2O_3) \cdot 10SiO_2$.

If $Mg : Fe = 7 : 2$, the percentage composition is: SiO_2 49.4, Al_2O_3 33.6, FeO 5.3, MgO 10.2, H_2O 1.5 = 100. Manganese and calcium may be present in small amounts.

Alteration.—Only partially decomposed by acids. Cordierite alters readily by hydration and chemical replacement. The alteration in some cases begins along planes parallel to (001) and results in a lamination of the crystal and finally an unlaminated aphanitic mass; in others it also takes place in planes parallel to (010), or less often in those parallel to the prism, and from irregular cracks. The resulting minerals are usually mica; mostly muscovite, besides biotite, paragonite, and chlorite, accompanied by iron oxides. These pseudomorphs after cordierite have received various names, according to their composition or appearance. Of these four types may be noted: *pinite*, chiefly mica, without lamination parallel to (001); *gigantolite*, the same, with basal lamination; *prasiolite*, chiefly chlorite,

without basal lamination; *chlorophyllite*, chiefly chlorite, with basal lamination.

Orthorhombic; $a:b:c=0.5871:1:0.5585$, (110) $(1\bar{1}0)=60°\ 50'$.

Euhedral crystals are short prisms with $a(100)$, $b(010)$, $c(001)$, $m(110)$, $d(130)$, $s(112)$, $r(111)$, $u(134)$, $o(131)$ (Fig. 1). Commonly in penetration twins with pseudohexagonal forms. Subhedral and anhedral crystals frequent.

Twinning.—(1) Parallel to (110) often repeated, producing pseudohexagonal forms; also as inclosed twinned lamellæ. (2) Parallel to (130) also producing pseudohexagonal forms, since (130) $(1\bar{3}0)=59°\ 10'$.

Cleavage parallel to (010) distinct; parallel to (100) and (001) indistinct. Crystals often show a lamellar structure parallel to (001), especially when partly altered. Fracture subconchoidal. H.=7–7.5. Sp. gr.=2.60–2.66.

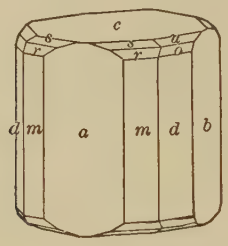


Fig. 1.

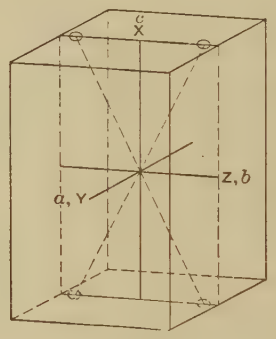


Fig. 2.

Optical Properties.—Optically negative (−); axial plane parallel to (100); acute bisectrix X normal to (001); $X \parallel c$, $Y \parallel a$, $Z \parallel b$, Fig. 2. Angle between the optic axes quite variable. Dispersion weak, $\rho<v$, according to Des Cloizeaux. For orange, $2V=39°\ 32'$, Haddam, Conn.; 70° 23′, Ceylon; 77° 57′, Orijärfvi; 84° 28′, Bodenmais. Refraction and double refraction variable in cordierite from different localities.

Tvedestrand	$\alpha_y=1.532$	$\beta_y=1.536$	$\gamma_y=1.539$	$\gamma-\alpha=0.007$	Lévy-Lacroix
Orijärfvi	$\alpha_{or}=1.5337$	$\beta_{or}=1.5375$	$\gamma_{or}=1.5400$	$=0.0063$	Des Cloizeaux
Bodenmais	$\alpha^y=1.5349$	$\beta_y=1.5400$	$\gamma_y=1.5440$	$=0.0091$	Zimanyi
"	$\alpha_{or}=1.535$	$\beta_{or}=1.541$	$\gamma_{or}=1.546$	$=0.011$	Des Cloizeaux
"	$\alpha_y=1.5433$	$\beta_y=1.5467$	$\gamma_y=1.5490$	$=0.0057$	Koch
Ceylon	$\alpha_{or}=1.537$	$\beta_{or}=1.542$	$\gamma_{or}=1.543$	$=0.006$	Des Cloizeaux
Haddam	$=1.5523$	$=1.5615$	$=1.5627$	$=0.0104$	"
Ceylon	$\alpha_y=1.5918$	$\beta_y=1.5970$	$\gamma_y=1.5992$	$=0.0074$	Offret

Color.—Various shades of blue, light or dark, smoky blue, also grayish, yellowish. In thin section colorless, or faintly pleochroic; in thicker sections distinctly pleochroic. The pleochroism becomes stronger upon heating the crystal. Luster vitreous. Absorption, $Y>Z>X$.

	X	*Y*	*Z*	
Haddam	yellowish white	pale blue	bluish white	Haidinger
Bodenmais	yellowish white	dark Berlin blue	light Berlin blue	Haidinger
"	yellowish to wine-yellow white	milk-white	greenish white	Haidinger
Hoyazo	yellowish white	dark violet	light violet	Osann
Ceylon	very light yellow	deep violet-blue	pale violet-blue	Offret
Simiutak	smoky brownish	dark leather-brown	reddish brown to honey-yellow	Haidinger
Arendal	reddish clove-brown	plum-blue	violet-blue	Haidinger
Orijärfvi	reddish clove-brown	dark Berlin blue	light Berlin blue	Haidinger

Inclusions.—In cordierite in the crystalline schists and in zones of contact metamorphism there are pleochroic spots surrounding microscopic inclusions, which are bright yellow when transmitted light vibrates parallel to the crystal axis *c*, but are colorless when the light vibrates parallel to the *a* or *b* axes. These pleochroic "halos" disappear on heating and are probably due to the segregation of organic pigment about the inclusions. Hence the absence of such "halos" from cordierite in the igneous rocks.

Cordierite is commonly quite free from characteristic inclusions, especially when found in igneous rocks. It sometimes contains fluid and gas inclusions, and when in rhyolite, glass inclusions. The cordierite in the crystalline schist often contains crystals of minerals associated with it, except garnet. It frequently incloses prismatic or fibrous crystals of sillimanite, sometimes regularly arranged, sometimes in a confused felt-like swarm. In other cases it incloses green spinel. In hornfels in Japan the cordierite sometimes is filled with inclusions of carbonaceous matter arranged in a manner somewhat similar to that in chiastolite.

Occurrences.—Cordierite occurs chiefly in gneiss and other crystalline schists also in zones of contact metamorphism, less often in igneous rocks. In gneiss and schist it is widespread, being found in many localities. As a product of contact metamorphism it occurs in the altered schists near Barr and Andlau in the Vosges; in Saxony; in the Troas; and in altered slate in the Watarase-gawa region, Japan, where it has the chiastolite-like inclusions. It is found in ejected blocks inclosed in lava at Laacher See, and at Asamayama, Japan. It is developed in sandstone vitrified by contact with basalt, and in sediments altered by burning coal seams in Commentry, France, and in Montana and elsewhere.

Cordierite is developed as a pyrogenetic mineral in some igneous rocks, especially granite. It has been found in andesite and dacite in Hungary; in rhyolite at Campiglia Maritima, Tuscany; in kersantites at Michaelstein in the Harz, and elsewhere.

Resemblances.—Cordierite in rock sections is most like quartz in refraction and double refraction, but is distinguished by its biaxial character.

Laboratory Production.—Cordierite has been obtained by fusing its constituents in an open crucible and by slow cooling. The resulting crystalline mass was composed of a magnesian pyroxene and crystals having the properties of cordierite (Bourgeois). It has also been obtained from the fusion of an andesitic magma (Morozewicz).

STAUROLITE.

$2H_2O \cdot 6(Fe,Mg)O \cdot 12Al_2O_3 \cdot 11SiO_2$ (?)

or $HFeAl_5Si_2O_{13}$.

Composition variable. Mn is sometimes present. Frequently impure by reason of numerous inclusions.

	Sp. gr.	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	H_2O	TiO_2		
St. Gothard	3.706	29.46	52.29	—	13.42	2.29	1.42	0.56	=	99.44
								CaOMnO		
Franklin, N. C.	3.711	27.91	52.92	6.87	7.80	3.28	1.59	tr.	=	100.37

Imperfectly decomposed by sulphuric acid. Alterations rare; sometimes changes to chlorite and a green mica.

Orthorhombic; $a:b:c = 0.4734:1:0.6828$.

Euhedral crystals short prisms with $b(010)$, $m(110)$, $c(001)$, and sometimes $r(101)$, Fig. 1. Commonly in cruciform twins. Crystals with rounded edges, seldom in anhedral grains.

Twinning.—(1) Twinning plane (032), cruciform twins crossing nearly at right angles (Fig. 2). (2) Twinning plane (232) crossing

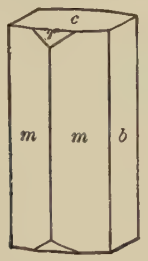


Fig. 1.

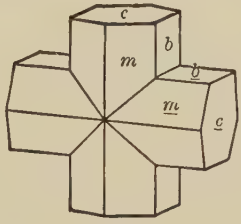


Fig. 2.

at an angle of 60° approx. (Fig. 3). (3) Twinning plane (230) rare, the b axes making an angle of 70° 45½′. Occasionally the twinning takes place without affecting the outward form of the crystal and is recognized by the optical behavior of the parts.

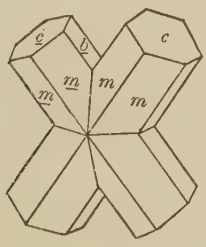


Fig. 3.

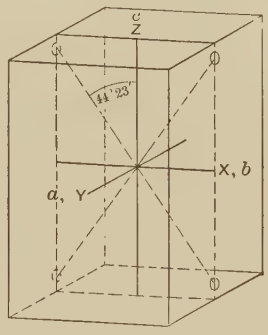


Fig. 4.

Cleavage.—Distinct parallel to (010), but interrupted; in traces parallel to (110). Fracture subconchoidal. H. = 7–7.5. Sp. gr. = 3.65–3.75.

Optical Properties.—Optically positive (+); plane of the optic axes parallel to (100); acute bisectrix Z normal to (001). $X \parallel b$, $Y \parallel a$, $Z \parallel c$ (Fig. 4). $2V_r = 88° 46'$, Lévy and Lacroix. Dispersion weak, $\rho > v$. Refraction high, double refraction low.

St. Gothard, $\alpha = 1.736$, $\beta = 1.741$, $\gamma = 1.746$, $\gamma - \alpha = 0.010$, Lévy-Lacroix. $\beta_r = 1.749$, Des Cloizeaux; $\beta_r = 1.7526$, Miller.

Color.—Dark reddish brown to brownish black and yellowish brown. In thin section yellow to red-brown. Pleochroism distinct: $X = Y$ yellowish red, often with a greenish tint; Z hyacinth-red to blood-red in thick plates. $X = Y$ whitish yellow, Z reddish yellow,

according to Rosenbusch. The color is often more intense around inclusions. Luster subvitreous to resinous.

Inclusions are very common in staurolite. Usually they consist of the minerals with which it is associated: quartz, sometimes as much as 30 or 40 per cent. of the whole; garnet, mica, tourmaline, rutile, etc. In some occurrences it is filled with carbonaceous matter like chiastolite, with which it is sometimes associated. In rarer instances—Lisbon and Charlestown, N. H., and Mur-en-Plouigneau and Forges Neuves, Brittany—the carbonaceous inclusions are regularly arranged, producing a tessellated appearance in cross-section, as in chiastolite. Staurolite is sometimes intergrown with cyanite in parallel orientation.

Occurrences.—Staurolite occurs in the crystalline schists, chiefly in mica-schist, phyllites, and gneiss, often accompanied by garnet, cyanite, and sillimanite. It is rarely developed in zones of contact metamorphism.

GRANDIDIERITE.

$7SiO_2 \cdot 11(Al,Fe)_2O_3 \cdot 7(Mg,Fe,Ca)O \cdot 2(Na,K,H)_2O$ (?)

Chemical Analysis.—SiO_2 20.90, Al_2O_3 52.80, Fe_2O_3 6.60, FeO 4.86, MgO 9.65, CaO 2.10, Na_2O 2.22, K_2O 0.40, H_2O 1.25 = 100.78. Unattacked by acids.

Orthorhombic (?).—Axial ratio not determined. Anhedral crystals, poikilitically intergrown with quartz, also massive.

Cleavage unequally developed parallel to two planes at right angles to each other, in the zone of the longest diameter of the crystals, and assumed to be (100) and (010). Sp. gr. = 2.99.

Optical Properties.—Optically negative (−). Acute bisectrix X is normal to (100), the plane of the better cleavage; plane of the optic axes parallel to (001). $X \parallel a$, $Y \parallel c$, $Z \parallel b$. $2E_r = 52°$, $2E_y = 49°\ 35'$. Dispersion strong, $\rho > v$.

$\alpha_y = 1.6018$, $\beta_y = 1.6360$, $\gamma_y = 1.6385$, $\gamma - \alpha = 0.0367$, Lacroix.

Refraction moderate, double refraction strong.

Color.—Bluish green; pleochroism strong. X deep blue-green, Y colorless Z deep green, in plates 0.5 mm. thick; X blue-green, Y colorless, Z pale bluish green, in thin section.

The phenomenon of absorption brushes is exhibited even in thin sections; blue brushes on colorless ground.

Occurrence.—Grandidierite occurs in pegmatites with quartz, orthoclase, and almandite, which it also incloses, near Fort Dauphin,

on the south point of Madagascar, material from which place has been studied and described by Lacroix.

KORNERUPINE (Prismatine).

$MgAl_2SiO_6$

Or $MgO \cdot Al_2O_3 \cdot SiO_2 = SiO_2$ 29.7, Al_2O_3 50.5, MgO 19.8 = 100. Insoluble in acids. Prismatine alters to a fibrous green mineral called kryptotile, a hydrous silicate of aluminium, $HAlSiO_4$.

Orthorhombic; $a:b = 0.854:1$.

Subhedral crystals of prismatic habit with (110), (100), and (010), and other less definite forms. Prismatic angle (110) $\wedge$ ($1\bar{1}0$) = 81° kornerupine, = 81° 31′ prismatine. Kornerupine occurs in fibrous to prismatic aggregates resembling sillimanite. Prismatine forms stout prisms in separate crystals or radiating groups.

Cleavage.—Prismatic rather perfect. Fracture uneven. H. = 6.5. Sp. gr. = 3.273 kornerupine; 3.341 prismatine.

Optical Properties.—Optically negative (−); acute bisectrix X normal to (001); axial plane parallel to (100). $X \parallel c$, $Y \parallel a$, $Z \parallel b$ (Fig. 1). $2E = 32°\ 30'$ and smaller to 14°, kornerupine; $2E_y = 65°\ 30'$, $2V_y = 37°\ 34'$, dispersion weak, $\rho > v$, prismatine, Ussing. Refraction moderate, double refraction low.

Prismatine, $\alpha_y = 1.6691$, $\beta_y = 1.6805$, $\gamma_y = 1.6818$, $\gamma - \alpha = 0.0127$, Ussing.

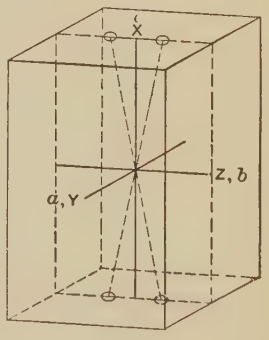


Fig. 1.

Color.—White, gray, yellowish to brownish, rarely greenish. In thin section colorless (kornerupine) or yellowish (prismatine). Pleochroism weak in prismatine. X clear wine-yellow, Y brownish yellow, Z greenish to colorless in sufficiently thick plates. Luster vitreous, to resinous on fractured surface.

Occurrence.—Kornerupine occurs on the west coast of Greenland, at Fiskernäs, in rock composed of sapphirine, hornblende, and mica; with some gedrite and cordierite, with which it is sometimes graphically intergrown. Prismatine occurs in granulite at Waldheim, Saxony, in layers of albite, associated with garnet and tourmaline.

Resemblances.—Kornerupine (prismatine) resembles sillimanite, andalusite, and topaz. It differs from sillimanite in the optical orientation with respect to the prismatic axis, and in the lower double

refraction; from andalusite by slightly higher refraction and smaller angle between the optic axes; from topaz by its cleavage.

SAPPHIRINE.

$Mg_5Al_{12}Si_2O_{27}$

Or $5MgO \cdot 6Al_2O_3 \cdot 2SiO_2$. SiO_2 12.9, Al_2O_3 65.7, MgO 21.4 = 100. A small amount of FeO may replace MgO. Not decomposed by acids.

Monoclinic; in indistinct tabular crystals, flattened parallel to (010), rarely showing prismatic planes on edges, $\beta = 79\frac{1}{2}°$. Usually in disseminated grains or lamellar aggregations.

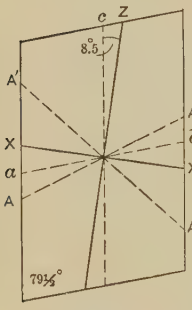


FIG. 1.

Cleavage not distinct. Fracture subconchoidal. H. = 7.5. Sp. gr. = 3.42–3.48.

Optical Properties.—Optically negative (−); plane of the optic axes parallel to (010); acute bisectrix X inclined to the crystal axis c 81.5° in the obtuse angle β. The obtuse bisectrix Z inclined to c 8.5° in acute angle β. $2V_y = 68° 49'$ (Fig. 1). Inclined dispersion very noticeable, $\rho < v$. Refraction high, double refraction low.

$\alpha_r = 1.705$, $\beta_r = 1.709$, $\gamma = 1.711$, $\gamma_r - \alpha_r = 0.006$, Des Cloizeaux.
$\alpha_r = 1.7055$, $\beta_r = 1.7088$, $\gamma = 1.7112$, $\gamma_r - \alpha_r = 0.0057$, Ussing.
— $\beta_y = 1.712$, — $\gamma_y - \alpha_y = 0.0058$, Ussing.

Color.—Pale blue or green; pleochroic in plates of some thickness. X colorless, $Y = Z$ blue; also X light greenish blue, Y dark blue-green, Z yellowish faded green. Luster vitreous.

Occurrence.—Sapphirine forms small lenticular masses in mica-schist and gneiss at Fiskernäs, Greenland. It is associated with hornblende, gedrite, and biotite, the sapphirine and biotite being so oriented that their tabular crystals are parallel to one another; with these are also cordierite, anorthite, and kornerupine. Or the sapphirine is accompanied only by bronzite and dark-green spinel.

Resemblances.—Sapphirine is like serendibite, cyanite, lazulite, lawsonite, and cordierite, to some extent. It is distinguished from serendibite by the absence of polysynthetic twinning; from cyanite by the absence of cleavage and lower double refraction; from lazulite and lawsonite by lower double refraction; from blue cordierite by its higher index of refraction.

CARPHOLITE.

$H_4MnAl_2Si_2O_{10}$

Or $2H_2O \cdot MnO \cdot Al_2O_3 \cdot 2SiO_2 = SiO_2$ 36.5, Al_2O_3 31.0, MnO 21.5, H_2O 11.0 = 100. FeO, MgO, and Fe_2O_3 are present in small amounts. Not decomposed by hydrochloric acid.

Monoclinic; $(110) \wedge (1\bar{1}0) = 68° 33'$. Subhedral crystals developed only in one prismatic zone. Twinning plane parallel to (100). In acicular or fibrous crystals, sometimes radiating.

Cleavage not noticeable, very brittle. H. = 5–5.5. Sp. gr. = 2.935.

Optical Properties.—Optically negative (−); acute bisectrix X normal to (010); bisectrix Z inclined to prism axis c 3° to 5°, Lévy-Lacroix. $2V = 60°$ approx.; $n = 1.627$, $\gamma - \alpha = 0.022$.

Color.—Pure straw-yellow to wax-yellow, green. In thin section colorless, yellowish, greenish. Distinctly pleochroic: $X = Y$ yellow-green to yellow, Z colorless. Luster silky, glistening.

Occurrence.—Carpholite occurs in minute tufts with fluorite and quartz in granite in the tin mines of Schlackenwald; on quartz veins at Wippra in the Harz; and with quartz in two localities in France.

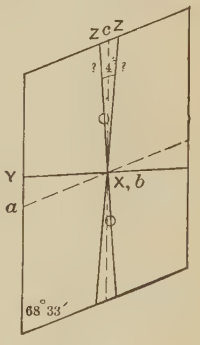


Fig. 1.

Resemblances.—Carpholite resembles sillimanite in refraction, double refraction, and crystal habit, but differs from it in the system of crystallization, being monoclinic.

ILVAITE (Lievrite).

$CaFe_2^{II}(FeOH)^{III}(SiO_4)_2$.

Chemical Composition.—A basic orthosilicate of calcium and iron, in which manganese may replace part of the ferrous iron. For $H_2O \cdot 2CaO \cdot 4FeO \cdot Fe_2O_3 \cdot 4SiO_2$ there would be SiO_2 29.3, Fe_2O_3 19.6, FeO 35.2, CaO 13.7, H_2O 2.2 = 100. In ilvaite from Nassau 8.66 MnO is present. Gelatinizes with hydrochloric acid.

Orthorhombic; $a:b:c = 0.6665:1:0.4427$.

Euhedral crystals prismatic parallel to c axis, and with the prism faces striated. Forms $b(010)$, $m(110)$, $s(120)$, $o(111)$, $r(101)$ (Fig. 1), and others. Anhedral crystals in prismatic aggregates, or irregularly shaped.

Cleavage parallel to (010) and (001) rather distinct; parallel to (100) indistinct; parallel to (110) and (101) imperfect. Fracture uneven. H.=5.5–6. Sp. gr.=3.99–4.05.

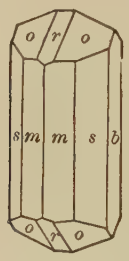


Fig. 1.

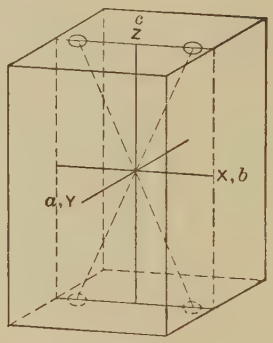


Fig. 2.

Optical Properties.—Optically positive (+); plane of the optic axes parallel to (100); acute bisectrix Z normal to (001). $X \parallel b$, $Y \parallel a$, $Z \parallel c$ (Fig. 2). Angle between the optic axes, $2V$, large on ilvaite from Greenland, Lorenzen. $2E=60°$ approx. Algeria. Refraction high, $\beta=1.89$, Wülfing.

Color.—Iron-black, dark grayish black. Streak black inclining to green or brown. In very thin portions transparent with brown or green colors. Pleochroism distinct: X brownish yellow, Y brown, Z green. $Z>Y>X$. Z and Y almost completely absorbed. According to Böggild, ilvaite is pleochroic in reflected light: X and Y brownish, Z greenish. Luster submetallic.

Occurrence.—Ilvaite occurs in dolomite with pyroxene on Elba; in Devonian shales altered in contact with diabase in Nassau; in limestone with actinolite in Tuscany, and elsewhere in metamorphosed sedimentary rocks. It also occurs as an alteration-product of arfvedsonite and ægirite in granite, syenite, and nephelite-syenite in Greenland and in other localities. Reported to have been found at Cumberland, R. I., in quartz with magnetite and hornblende, and at Somerville, Mass.

The wool-like fibrous mineral *breislakite*, found at Vesuvius and Capo di Bove, is referred to ilvaite by Weinschenk.

CHLOROPAL.

(?) $H_6Fe_2(SiO_4)_3+2H_2O$.

Chemical Composition.—Hydrated iron silicate, perhaps with the formula given. $Fe_2O_3 \cdot 3SiO_2 \cdot 5H_2O = SiO_2$ 41.9, Fe_2O_3 37.2, H_2O 20.9 = 100. Alumina is present in some varieties. *Chloropal* is partially decomposed by hydrochloric acid; the variety known as *pinguite* is completely decomposed with the separation of pulverulent silica; *nontronite* gelatinizes with hydrochloric acid.

Monoclinic; compact massive with an opal-like appearance; also earthy. Composed of microscopic plates or laminæ like mica in radiating aggregates.

Cleavage distinct parallel to the surface of the plate (001); also parallel to a prism (110) with angle of 63°–64°. Fracture conchoidal to splintery. Feebly adhering to the tongue, and meager to the touch. Fragile. *Nontronite* has an unctuous feel, flattens and grows lumpy under the pestle, and is polished by friction. *Pinguite* is extremely soft, like new-made soap, with a slightly resinous luster, not adhering to the tongue. H. = 1–2 nontronite, 2.5–4.5 chloropal. Sp.gr. = 2.105 chloropal, Ceylon; 2.08–2.35 nontronite, St. Pardoux.

Optical Properties.—*Nontronite*, optically negative (−), acute bisectrix X normal to laminæ, Lacroix; according to Weinschenk it is inclined 5°–6° to this normal; $2E = 55°$ approx. Lacroix. Double refraction strong, $\gamma - \alpha = 0.020$ at least.

Color.—*Chloropal:* greenish yellow and pistachio-green. *Nontronite:* straw-yellow, canary-yellow to greenish; pleochroism slight, yellowish parallel to the lamellar cleavage, yellow-green to greenish yellow at right angles to it. Luster dull or glistening.

Occurrence.—*Chloropal* occurs like clay at Unghwar, Hungary. *Nontronite* is found partly along ore veins, as at Nontron, near St. Pardoux, France; or along fissures as an alteration product of granitic rocks. At Passau it is associated with graphite and is traversed by asbestus and hornblende. Other varieties of this mineral with slightly different physical aspect are *fettbol*, liver-brown, and *graminite*, grass-green.

TOURMALINE.

$$\overset{\text{I}}{R}_6SiO_5.$$

Chemical Composition.—A complex silicate of aluminium and boron, with magnesium, iron, or the alkalies prominent. Formula uncertain; possibly $\overset{\text{I}}{R}_6SiO_5 = \overset{\text{II}}{R}_3SiO_5 = \overset{\text{III}}{R}_2SiO_5$, in which $\overset{\text{I}}{R}$ = Na, Li, K, H; $\overset{\text{II}}{R}$ = Mg, Fe, Ca; $\overset{\text{III}}{R}$ = Al, B, Cr, Fe. Or it may be a mixture of the molecules:

$$12SiO_2 \cdot 3B_2O_3 \cdot 8Al_2O_3 \cdot 2Na_2O \cdot 4H_2O,$$
$$12SiO_2 \cdot 3B_2O_3 \cdot 5Al_2O_3 \cdot 12MgO \cdot 3H_2O.$$

The various tourmalines differ in the proportions of the constituents, and may be classed as alkali-tourmalines, iron-tourmalines, magnesium-tourmalines, also chromium-tourmaline. The composition of a few of them are shown in the analyses.

Alteration.—Not decomposed by acids. Alteration to mica, muscovite, lepidolite, and biotite, also to chlorite, has been described. In rock sections it apppears unaltered.

Trigonal; ditrigonal-pyramidal class. $c = 0.44767$.

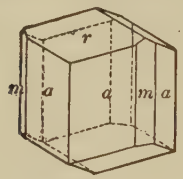


Fig. 1.

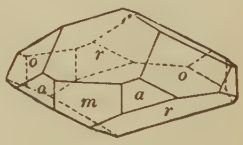


Fig. 3.

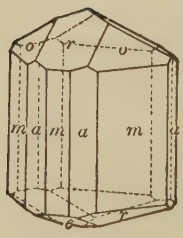


Fig. 2.

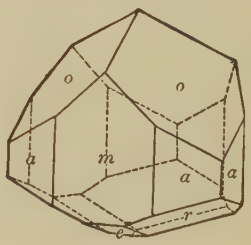


Fig. 4.

Euhedral crystals commonly prismatic, often slender to acicular, also short and thick, rarely flattened. The planes developed are

Chemical Analyses of Tourmaline.

		Sp. gr.	SiO_2	TiO_2	B_2O_3	Al_2O_3	Fe_2O_3	FeO	MnO	CaO	MgO	Na_2O	K_2O	Li_2O	H_2O	F	
Rumford, Me	rose	2.997	38.07	—	9.99	42.24	—	0.26	0.35	0.56	0.07	2.18	0.44	1.59	4.26	0.28	=100.29
Auburn, Me.	colorless	3.07	38.14	—	10.25	39.60	0.30	1.38	1.38	0.43	—	2.36	0.27	1.34	4.16	0.62	=100.23
Auburn, Me.	pale green	—	37.85	—	10.55	37.73	0.42	3.89	0.51	0.49	0.04	2.16	0.62	1.34	4.18	0.62	=100.39
Rumford, Me.	dark green	—	36.53	?	10.22	38.10	—	6.43	0.32	0.34	—	2.86	0.38	0.95	3.52	0.16	= 99.81
Auburn, Me.	black	3.19	34.99	—	9.63	33.96	—	14.23	0.06	0.15	1.01	2.01	0.34	tr.	3.62	—	=100.00
Pierrepont, N. Y.	black	3.08	35.61	0.55	10.15	25.29	0.44	8.19	tr.	3.31	11.07	1.51	0.20	tr.	3.34	0.27	= 99.93
Gouverneur, N. Y.	brown	—	37.39	1.19	10.73	27.79	0.10	0.64	—	2.78	14.09	1.72	0.16	tr.	3.83	tr.?	=100.42
De Kalb, N. Y.	colorless	3.085	36.88	0.12	10.58	28.87	—	0.52	—	3.70	14.53	1.39	0.18	tr.	3.56	0.50	=100.83

usually $a(11\bar{2}0)$, $m(10\bar{1}0)$ with $h(41\bar{5}0)$ subordinate; and $r(10\bar{1}1)$, $o(02\bar{2}1)$, sometimes $x(12\bar{3}2)$, $c(0001)$, and other forms, Figs. 1, 2, 3, and 4. Prismatic faces often striated parallel to the c axis. Anhedral crystals usually prismatic or irregularly shaped, often in radiating groups. Cross sections of prisms characteristically trigonal, three-sided or nine-sided, more or less rounded.

Cleavage not noticeable, or difficult parallel to $(11\bar{2}0)$ and $(10\bar{1}1)$. Fracture subconchoidal to uneven. H.=7–7.5. Sp. gr.=2.98–3.20.

Optical Properties.—Optically negative (−). Sometimes anomalously biaxial, from molecular strain, probably the result of pressure. Refraction and double refraction moderate, varying with the composition. According to Wülfing the lithium-tourmalines have the lowest refraction, with intermediate double refraction; the magnesium-tourmalines have intermediate refraction and the lowest double refraction; the iron-tourmalines the highest refraction, and double refraction.

		ω_y	ϵ_y	$\omega - \epsilon$	
Elba	colorless	1.6397	1.6208	0.0189	Miklucho-Maclay
"	"	1.6386	1.6202	0.0184	Zimanyi
"	"	1.6424	1.6223	0.0201	Wülfing
Haddam	green	1.6401	1.6220	0.0181	"
Brazil	dark green	1.6424	1.6222	0.0202	Zimanyi
Ural	blue	1.6530	1.6312	0.0218	Schwebel
Tyrol	black	1.6429	1.6195	0.0234	Zimanyi
		ω_{gr}	ϵ_{gr}		
Syssert	(chromium)	1.6870*	1.6412	0.0458	Arzruni

*Approx.

Color.—Black, brownish black, bluish black; also blue, green, red, rarely white or colorless. In thin section lighter shades of the colors named, with strong absorption or pleochroism. Colors vary zonally in some cases, from end to end in others. The absorption is always $O > E$, though the pleochroism in different varieties varies greatly.

Brown variety	O dark brown	E light yellow
Green variety	O dark green	E reddish violet to brownish
Blue variety	O blue in various tones	E pale reddish violet
Chromium-tourmaline	O green to blue-green	E yellow

Luster vitreous to resinous.

Occurrence.—Tourmaline is of wide-spread occurrence in crystalline schists and in the more siliceous igneous rocks, especially in

pegmatites and in the vicinity of veins. It is found in gneiss, mica-schists, granulites, and similar rocks, as well as in phyllites and clay-slates. It is common in zones of contact metamorphism occurring in the most varied kinds of rocks, resulting from impregnations by vapors from intruded igneous magmas, especially the more siliceous and alkalic, but also basaltic, such as the traps of New Jersey and elsewhere.

It frequently replaces mica and feldspars in granites subjected to gaseous exhalations along fissures or veins, as in greissen and tourmaline-granite, luxullianite, in Cornwall, and many other localities.

It also occurs as a pyrogenetic mineral in igneous rocks, particularly granites, pegmatites, and to a less extent in the corresponding porphyries and occasionally in lavas.

Resemblances.—Tourmaline is well characterized by the combination of its refraction, double refraction, pleochroism, uniaxial character, and lack of cleavage. When colorless it is like apatite in refraction, but has much stronger double refraction.

DATOLITE.

$HCaBSiO_5$.

Chemical Composition.—A basic orthosilicate of calcium and boron, $H_2O \cdot 2CaO \cdot B_2O_3 \cdot 2SiO_2$, yielding SiO_2 37.6, B_2O_5 21.8, CaO 35.0, H_2O 5.6 = 100. Gelatinizes with hydrochloric acid.

Monoclinic; $a:b:c = 0.63446:1:1.26574$, $\beta = 89° 51\frac{1}{3}'$. Euhedral crystals commonly nearly equidimensional with numerous faces, habit not characteristic. Anhedral crystals in irregularly shaped grains, also in botryoidal and globular aggregations with prismatic or radially fibrous structure.

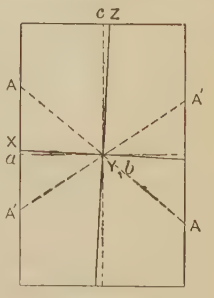


FIG. 1.

Cleavage not observed. Fracture conchoidal to uneven. H. = 5–5.5. Sp. gr. = 2.9–3.0.

Optical Properties.—Optically negative (−); plane of the optic axes parallel to (010); acute bisectrix X nearly normal to (100). Inclination of Z to c axis = 1°–4° in the acute angle β; from 0° 51′–4° 46′ on crystals from Bergen Hill. Angle between the optic axes large; dispersion weak and inclined; $\rho > v$.

$2V_y = 74° 22'$, Andreasberg, Des Cloizeaux; $74° 8'$, Bergen Hill, Brugnatelli. Refraction moderate, double refraction strong.

Andreasberg, $\alpha_y = 1.6260$, $\beta_y = 1.6535$, $\gamma_y = 1.6700$, $\gamma - \alpha = 0.0440$, Des Cloizeaux.

Bergen Hill, $= 1.6246$, $= 1.6527$, $= 1.6694$, $= 0.0448$, Brugnatelli.

Color.—Colorless, white, sometimes grayish, greenish yellow, red, or amethystine; rarely dirty olive-green or honey-yellow. In thin section colorless.

Occurrence.—Datolite occurs as a secondary mineral in cavities and cracks in basic igneous rock, basalts, gabbros, etc., and also in gneiss and amphibolite. It is found associated with zeolites, prehnite, calcite, and other minerals in trap at various localities in Scotland, Germany, and the United States. It also occurs to some extent in zones of contact metamorphism, as in graptolite-schist in contact with diabase near Listitz, where it forms a porcelain-like adinole; also as a contact product in Dartmoor Forest, Devonshire, forming a garnet-datolite-hornfels.

Resemblances.—Datolite resembles topaz, andalusite, monticellite, and wollastonite in refraction, but differs from them in its strong double refraction. It is also similar to prehnite in refraction, but has a still higher double refraction.

AXINITE.

$Ca_7Al_4B_2(SiO_4)_8$.

Chemical Composition.—A borosilicate of calcium and aluminium, in which calcium may be replaced in part by manganese, and to a smaller extent by iron, magnesium, and basic hydrogen. Ferric iron is also present.

	Sp. gr.	SiO_2	B_2O_3	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	
Bourg d'Oisans	—	41.53	4.62	17.90	3.90	4.02	3.79	0.74	21.66	
								ign 2.16	= 100.32	
						ZnO				CuO
Franklin Furnace	3.358	42.77	5.10	16.73	1.03	1.48	13.69	0.23	18.25	0.12
								ign 0.76	= 100.16	

Not decomposed by acids.

Triclinic; $a:b:c = 0.49211:1:0.47970$; $\alpha = 82° 54' 13''$, $\beta = 91° 51' 43''$, $\gamma = 131° 31' 19''$.

Euhedral crystals usually broad and acute-edged, but varied

in habit. Planes present in simpler crystals $M(1\bar{1}0)$, $m(110)$, $r(1\bar{1}1)$, $s(201)$, $a(100)$, $x(111)$, (Fig. 1). Flattened parallel to $(1\bar{1}0)$, (110) or $(1\bar{1}1)$; rarely prismatic parallel to the c axis. Faces often striated parallel to the zone Mam, also Msx. Face r usually striated parallel to the edge rM. Anhedral crystals sometimes lamellar or granular.

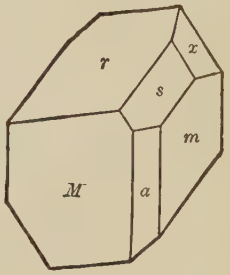


FIG. 1.

Cleavage parallel to (010) distinct; also parallel to (001) and $(1\bar{3}0)$; less perfect in other directions. Fracture conchoidal. H.= 6.5–7. Sp. gr.=3.271–3.294.

Optical Properties.—Optically negative (−); acute bisectrix X nearly normal to $x(111)$, on which plane the trace of the plane of the optic axes is inclined 40° to the edge $(\bar{1}11)(1\bar{1}0)$, and 24° 40′ to the edge $(111)(1\bar{1}1)$, Des Cloizeaux. The angle $2V$ is large, but somewhat variable in the same crystal. Dispersion pronounced, $\rho < v$; inclined and horizontal, $2V_r = 71°\ 38'$, $2V_{bl} = 71°\ 49'$. $2E_r = 158°\ 13'$, $2E_{bl} = 165°\ 38'$. Refraction moderately high; double refraction low.

$\alpha_\rho = 1.6720$, $\beta_\rho = 1.6779$, $\gamma_\rho = 1.6810$, $\gamma_\rho - \alpha_\rho = 0.0090$, Des Cloizeaux.
$\alpha_v = 1.6850$, $\beta_v = 1.6918$, $\gamma_v = 1.6954$, $\gamma_v - \alpha_v = 0.0104$, "

Color.—Clove-brown, plum-blue, pearl-gray; also honey-yellow, greenish yellow, peach-blossom red. In thin section colorless, very pale yellowish, pale gray-brown or violet. Pleochroic in thick plates, X pale olive-green to colorless, Y dark violet-blue, Z cinnamon-brown.

Occurrence.—Axinite occurs in cavities in some granite and diabase and in zones of metamorphism in contact with these rocks. It is especially developed in certain contact rocks in the Pyrenees called limurite, which in the Valley of Lesponne consist of axinite, augite, hornblende, with quartz, calcite, titanite, and iron oxides. Similar axinite-rocks have been found in Tasmania and South Australia. It occurs at Franklin Furnace, N. J., with rhodonite, polyadelphite, and basite; and elsewhere.

Resemblances.—Axinite is well characterized by its crystal habit, cleavage, and optical properties; strong refraction and low double refraction.

SERENDIBITE.

$(Mg,Ca,Fe)_{10}B_2Al_{10}Si_6O_{40}$.

Chemical Composition.—SiO_2 25.33, Al_2O_3 34.96, B_2O_3 4.17 (by difference), FeO 4.17, MgO 14.91, CaO 14.56, Na_2O+Li_2O 0.51, K_2O 0.22, P_2O_5 0.48, ign. 0.69 = 100. Not attacked by acids.

Triclinic or **Monoclinic.**—In grains and six-sided plates, elongated in the direction of one pair of edges. Polysynthetically twinned, parallel to the longer pair of edges, like lime-soda-feldspar.

Cleavage wanting. Fracture subconchoidal. H. = 7 approx. Sp. gr. = 3.42.

Optical Properties.—Optically positive (+). In sections at right angles to the twinning plane, with symmetrical extinction angles in the twinned lamellæ of 35°–40°, the acute bisectrix Z is allmost normal to the section. The angle $2V$ is large (Coomáraswámy). Refraction about 1.7; double refraction weak.

Color.—Blue, from light azure-blue to deep indigo-blue; strongly pleochroic between pale yellowish green to colorless and azure-blue, or between brownish yellow and deep indigo-blue.

Occurrence.—Serendibite occurs with diopside, green spinel, and occasionally small amounts of scapolite and lime-soda-feldspar in a layer 1.25–2.5 cm. thick, together with a layer of diopside between granulite and crystalline limestone at the moonstone quarries near Gangapitiya, twelve miles east of Kandy, Ceylon.

Resemblances.—Serendibite is distinguished from other blue minerals of like refraction and double refraction by its polysynthetic twinning.

HELVITE—DANALITE.

HELVITE, $(Mn,Fe)_2(Mn_2S)Be_3(SiO_4)_3$.
DANALITE, $(Fe,Zn,Mn)_2((Zn,Fe)_2S)Be_3(SiO_4)_3$.

HELVITE.

Chemical Composition.—Formula as given above. According to the proportions of Mn and Fe there is a difference in color and other properties.

Ilmen Mountains near Miask, dark reddish brown, Sp. gr. 3.33.

SiO_2 32.49, BeO 13.52, MnO 35.41, FeO 15.12, S 5.77, Al_2O_3 0.77 = 103.08.

Amelia Court-house, Va., sulphur-yellow, Sp. gr. 3.25.

SiO_2 31.42, BeO 10.97, MnO 40.56, FeO 2.99, Mn 8.59, S 4.90, Al_2O_3 0.36 = 99.79.

Decomposed by hydrochloric acid with evolution of hydrogen sulphide and separation of gelatinous silica.

Isometric System.—Hextetrahedral. Common forms tetrahedrons, rarely rhombohedrons, other forms subordinate; also in spherical masses.

Cleavage.—Octahedral in traces. Fracture uneven to conchoidal. H. = 6–6.5. Sp. gr. 3.16–3.36 according to composition. Pyroelectric.

Optical Properties.—Isotropic. $n = 1.739$, Langesund fjord, Lévy and Lacroix, about the same as grossularite garnet. *Color:* honey-yellow, yellowish brown, siskin-green, reddish brown. In thin section yellow to colorless.

Modes of Occurrence.—Helvite occurs in augite-syenite pegmatite in Norway and in granite pegmatites in the Urals and in Virginia, and in gneiss in Saxony.

DANALITE.

Chemical Composition.—Formula as given above. Danalite from Rockport, Mass: SiO_2 31.73, FeO 27.40, MnO 6.28, ZnO 17.51, BeO 13.83, S 5.48 = 102.23 less (O = S) 2.74 = 99.49. Decomposed by hydrochloric acid with evolution of hydrogen sulphide and separation of gelatinous silica.

Isometric System.—Crystallizes in octahedrons, sometimes with dodecahedral faces, striated parallel to (110)(111). Fracture subconchoidal to uneven. H. = 5.5–6. Sp. gr. = 3.427.

Optical Properties.—Isotropic. Color flesh-red to gray. Luster vitreo-resinous.

Mode of Occurrence.—Danalite occurs in small grains disseminated in the granite at Rockport, Cape Ann, Mass., also in the granite near Gloucester, Mass. It is associated with lepidolite at both localities. It occurs with magnetite and quartz at Bartlett, N. H.

MELIPHANITE (Melinophane).

$NaCa_2Be_2FSi_3O_{10}$.

Chemical Composition.—A fluosilicate of beryllium, calcium, and sodium near leucophanite. SiO_2 46.9, BeO 13.1, CaO 29.1, Na_2O 8.1, F 5.0 = 102.2, deduct 2.2 (O = 2F) = 100. Aluminium may also be present. Insoluble in acids.

Tetragonal; bisphenoidal class. $c = 0.65843$.

Euhedral crystals commonly obtuse bipyramids with (111) prominent, and subordinate bisphenoids; the low symmetry also shown by the etching figures; also tabular with (001) prominent. Anhedral crystals sometimes composed of plates or lamellæ, probably due to polysynthetic twinning on (001).

Cleavage parallel to (001) distinct. H. = 5–5.5. Sp. gr. = 3.006–3.018.

Optical Properties.—Optically negative (−). In places anomalously biaxial. Refraction moderate, double refraction strong. As determined by Brögger:

$$\omega_r = 1.6097 \text{ (red glass)}, \quad \omega_y = 1.6126, \quad \omega_{gr} = 1.6161.$$
$$\varepsilon_r = 1.5912 \quad " \quad , \quad \varepsilon_y = 1.5934, \quad \varepsilon_{gr} = 1.5975.$$
$$\omega_y - \varepsilon_y = 0.0192.$$

Color.—Sulphur-, citron-, or honey-yellow; also flesh-red, brick-red. Pleochroism noticeable in thick sections. *O* honey-yellow to brownish yellow, *E* pale greenish yellow. Luster vitreous.

Occurrence.—Meliphanite is found in the nephelite-syenite pegamatites of the islands in the Langesund fjord and near Fredriksvärn, Norway. It is not associated with leucophanite, but appears to take its place in certain localities.

Resemblances.—Meliphanite is somewhat like the yellow minerals wöhlerite, låvenite, hiortdahlite. It differs from them all in being uniaxial, and in having somewhat lower refraction and double refraction, except in the case of hiortdahlite, whose double refraction is lower.

LEUCOPHANITE.

$Na(BeF)Ca(SiO_3)$.

SiO_2 49.4, BeO 10.3, CaO 23.0, Na_2O 12.8, F 7.9 = 103.4, deduct 3.4 (O = 2F) = 100.

Orthorhombic; bisphenoidal class. $a:b:c = 0.99391:1:0.67217$. Euhedral crystals rare, usually tabular parallel to (001) with (110) and bisphenoidal modifications. Occasionally prismatic parallel to (110).

Twinning plane (110). The crystals sometimes grown together along an irregular surface perpendicular to (001), producing fourlings of right- and left-handed crystals; also twins in which the composition plane is (001).

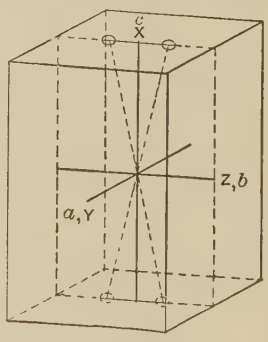


FIG. 1.

Cleavage.—Parallel to (001) perfect; parallel to (100) and (201) distinct, and also parallel to (010) and (021). This double cleavage and the value of the crystal axes a and b show the close relation of the mineral to the tetragonal symmetry exhibited by the chemically similar meliphanite. Fracture conchoidal. Very brittle. H. = 4. Sp. gr. = 2.959, Brögger.

Optical Properties.—Optically negative (−); plane of the optic axes parallel to (100); acute bisectrix X normal to (001); dispersion weak, $\rho > v$. $2V_y = 39° 2'$.

$2E_r = 74° 24\frac{1}{2}'$, $2E_y = 74° 15'$, $2E_{gr} = 74° 8'$, Brögger.
$\alpha = 1.5680$, $\beta_r = 1.5909$, $\gamma_r = 1.5948$, "
$\alpha_y = 1.5709$, $\beta_y = 1.5948$, $\gamma_y = 1.5979$, "
$\gamma_y - \alpha_y = 0.0270$.

Indices of refraction moderate, double refraction strong.

Color.—Whitish green, greenish white, deep green with a yellow tinge, wine-yellow. In thin section colorless. Luster vitreous. Strongly phosphorescent with a bluish light, whether heated or struck.

Occurrence.—Leucophanite occurs in pegmatite veins of nephelite-syenite on Låven, Stokö, and other islands in the Langesund fjord, Norway. It is closely related to meliphanite, occurring in the same kind of rocks, but not together.

EUDIALYTE (Eucolite).

$$\overset{I}{R}_4\overset{II}{R}_3Zr(SiO_3)_7.$$

Chemical Composition.— Formula as given above. $\overset{I}{R}$ = Na chiefly, also K, H; $\overset{II}{R}$ = Ca chiefly, also Fe, Mn, and Ce(OH); $ZrOCl_2$ in part replacing SiO_2. Niobium (tantalum) may be present in small amount.

	Sp. gr.	SiO_2	Ta_2O_5	ZrO_2	Ce_2O_3	FeO	MnO	CaO	Na_2O
Eudialyte, Greenland	—	48.63	—	14.49	2.27	5.54	0.42	10.57	15.90
				Cl 1.04, ign 1.91, MgO 0.15 = 100.92					
" Magnet Cove	2.810	51.83	0.39?	11.45	—	4.37	0.37	14.77	13.29
				K_2O 0.43, Cl 1.42, ign 1.88, MgO 0.11 = 100.31					
Eucolite, Barkevik	3.104	45.15	3.52	12.51	4.80	3.90	3.60	12.11	11.17
				K_2O 0.11, Cl 0.55, ign 2.11, Y_2O_3 0.32 = 99.85					

Gelatinizes with hydrochloric acid. Alteration to catapleite has been described by Ussing.

Trigonal; scalenohedral (?) class, $c = 2.1116$.

Euhedral crystals often tabular parallel to $c(0001)$, or rhombohedral and highly modified (eudialyte); also prismatic with $a(11\bar{2}0)$,

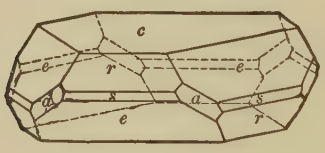


Fig. 1.

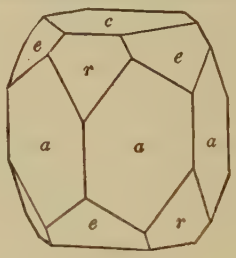


Fig. 2.

and $r(10\bar{1}1)$ large or small (eucolite), besides forms $c(0001)$, $e(01\bar{1}2)$, and others, Figs. 1 and 2. Anhedral crystals in irregularly shaped grains.

Cleavage.—In eudialyte perfect parallel to (0001); parallel to $(11\bar{2}0)$ and (1014) difficult; in eucolite most distinct parallel to (0001); imperfect parallel to $(11\bar{2}0)$ and $(10\bar{1}0)$. Fracture subconchoidal, splintery. H. = 5–5.5. Sp.gr. = 2.91–2.93 eudialyte; 3.0–3.1 eucolite.

Optical Properties.—Eudialyte is optically positive (+); eucolite is optically negative (−). In a variety from Umptek in some parts

positive, in others negative or zero (Ramsay). Refraction moderate, double refraction very low.

Eudialyte, Greenland	$\omega_r = 1.6042$	$\varepsilon_r = 1.6060$			Wülfing
	$\omega_y = 1.6084$	$\varepsilon^y = 1.6102$	$\varepsilon - \omega = 0.0018$		"
	$\omega_{gr} = 1.6120$	$\varepsilon_{gr} = 1.6142$			"
" Umptek, Kola	$\omega_y = 1.6104$	$\varepsilon_y = 1.6129$	$\varepsilon - \omega = 0.0025$		Ramsay
" Lujaur Mt.,	$\omega_r = 1.6018$	$\varepsilon_r = \omega_r$			
Kola	$\omega_y = 1.6057$	$\varepsilon_r = \omega_r$	$\varepsilon - \omega = 0$		Ramsay
	$\omega_{gr} = 1.6094$	$\varepsilon_r = \omega_r$			
Eucolite, Langesund	$\omega = 1.6205$	$\varepsilon = 1.6178$	$\omega - \varepsilon = 0.0027$		Brögger

Anomalously biaxial in crystals from Greenland, Kola, and Magnet Cove, the axial angle in air $2E$ reaching 50° in some instances. Hour-glass structure with differences in the double refraction is developed in some crystals from the Kola peninsula.

Color.—Rose-red, bluish red, brownish red, chestnut-brown. In thin section colorless, yellowish, rose, to light red. Sometimes zonally distributed. Pleochroism weak, scarcely perceptible in thin section. Absorption $O > E$. Luster vitreous.

Occurrence.—Eudialyte and eucolite are developed in nephelite-syenite, and in pegmatites of this rock and in its porphyry forms. Eudialyte occurs at Kangerdluarsuk, Greenland; at Umptek and Lujaur on the Kola peninsula, Finland; also at Magnet Cove, Ark., with eucolite, which occurs in the nephelite-syenites in the Langesund fjord, Norway. A eudialyte-like mineral also occurs in nephelite rocks on Madagascar and in Tasmania.

Resemblances.—Eudialyte and eucolite are somewhat like apatite and melilite in refraction and double refraction. The characteristic blue interference color of melilite is distinctive of that mineral. They are distinguished from apatite by the cleavage, and the habit of euhedral crystals, and eudialyte is further distinguished by its optical character.

ZIRCON.

$ZrSiO_4$.

Chemical Composition—$ZrO_2 \cdot SiO_2 = SiO_2$ 32.8, ZrO_2 67.2 = 100. A little Fe_2O_3 is usually present in analyses. Not acted on by acids, except in fine powder with concentrated sulphuric acid. Seldom observed in an altered condition in rock sections. By hydration it becomes isotropic and passes into a number of different alteration products.

Tetragonal; ditetragonal-bipyramidal class. $c=0.640373$. Euhedral crystals commonly short prisms, $m(110)$ or $a(100)$, or both, with $p(111)$, $u(331)$, and other bipyramids, also $x(311)$, Figs. 1–4. Less often in long prisms, or in short bipyramids rarely with (001).

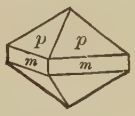


FIG. 1.

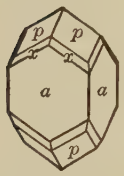


FIG. 2.

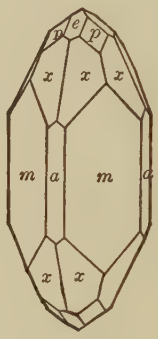


FIG. 3.

FIG. 4.

Anhedral crystals seldom observed in igneous rocks, but common in schists and sedimentary rocks.

Twinning and composition plane (101), geniculated as in rutile and cassiterite, but not developed in igneous rocks.

Cleavage parallel to (110) imperfect; parallel to (111) less distinct. Fracture conchoidal. H.=7.5. Sp. gr.=4.68–4.70 commonly, but varying from 4.2–4.86.

Optical Properties.—Optically positive (+). Abnormally biaxial in some large crystals. Refraction and double refraction high.

Ceylon	$\omega_y=1.9239$	$\varepsilon_y=1.9682$	$\varepsilon-\omega=0.0443$	Sanger
	$=1.960$	$=2.015$	$=0.055$	Brewster
Miask	$=1.9313$	$=1.9931$	$=0.0618$	Sanger

Microscopic crystals 0.01–0.02 mm. thick exhibit interference colors of the second order.

Color.—Colorless, pale yellowish, grayish, yellowish green, brownish yellow, reddish brown. In thin section colorless to light shades of the colors named, sometimes violet-blue. Sometimes zonally distributed. Pleochroism in strongly colored varieties, weak in comparatively thick plates, not noticeable in thin sections. Haidinger found on zircon from Ceylon; brownish gray, *O* clove-brown, *E* asparagus-green; pale clove-brown, *O* gray violet-blue, *E* gray olive-green; greenish white, *O* pale blue, *E* pale yellow. Luster adamantine.

Occurrence.—Zircon is wide-spread in small amounts in the more siliceous or alkalic feldspathic igneous rocks, reaching its greatest abundance in certain syenites of Norway. It occurs in granites,

syenites, nephelite-syenites, diorites, and in their corresponding porphyries and lava forms. It is rarely found in the basic igneous rocks, gabbros, peridotites, and rocks closely related to them. When in larger crystals it sometimes contains inclusions of other minerals and possibly apatite and glass. It is almost always euhedral, being one of the earliest crystals formed in the magma, occurring as inclusions in most other minerals. It is especially included or associated with magnetite, apatite, and biotite.

Zircon is also present in the crystalline schists of various kinds, and is developed in crystalline limestone, as at Grenville and elsewhere in Canada, associated with wollastonite and titanite.

Resemblances.—Zircon is well characterized by its crystal form and brilliant interference colors when in microscopic crystals or very thin sections. It resembles the much rarer minerals cassiterite and xenotime in crystal habit and high refraction, and xenotime in double refraction. It is distinguished from cassiterite by lower double refraction; from xenotime by chemical tests, or by its hardness.

Laboratory Production.—Zircon has been obtained by the action of silicon chloride on zirconia (Daubrée); by the action of silicon fluoride on zirconia, or of zirconium fluoride on quartz at a high temperature (Deville and Caron); also by heating gelatinous silica and zirconia at a red heat (von Chrustschoff).

THORITE.

$ThSiO_4 + aq.$

Chemical Composition.—Originally anhydrous. $ThO_2 \cdot SiO_2 = SiO_2$ 18.5, ThO_2 81.5 = 100. But all analyses show from 6 to 11 per cent of water, and sometimes as much as 9.78 per cent of uranium oxide, also iron. Becomes hydrated readily, when it is easily decomposed by hydrochloric acid.

Tetragonal; $c = 0.6402$. Crystal forms and habit like those of zircon. Also massive.

Cleavage parallel to (110) distinct. Fracture conchoidal. H. = 4.5–5. Sp. gr. = 4.4–4.8 thorite; 5.19–5.40 orangite.

Optical Properties.—Optically positive (+). Becomes isotropic upon alteration.

Color.—Orange-yellow, brownish yellow, also black. Streak light orange to dark brown.

Occurrence.—Thorite occurs in augite-syenite on the island of Lövö, and at other points on the Langesund fjord, Norway.

BECKELITE.

$Ca_3(Ce,La,Di)_4Si_3O_{15}$.

Or $3CaO \cdot 2(Ce,La,Di)_2O_3 \cdot 3SiO_2$, with very small amounts of ZrO_2, Y_2O_3, and alkalies. Soluble in hydrochloric acid.

Isometric System.—Euhedral crystals octahedral in habit; sometimes modified by (100) and (110); also in dodecahedrons and anhedral grains.

Cleavage.—Cubical. Fracture conchoidal. H. = 5. Sp. gr. = 4.15 approx.

Optical Properties.—Isotropic in small crystals, larger ones sometimes anomalously doubly refracting. Refraction high.

Color.—Wax-brown; in thin section light yellow. Luster vitreous.

Occurrence.—Beckelite occurs in an apophysis of mariupolite, consisting of granular albite with phenocrysts of nephelite and magnetite, from the Balka Wali-Tarama. (Morozewicz.)

Resemblance.—Beckelite is like pyrochlore, from which it is distinguished by its behavior toward acid.

MICA GROUP.

Composition: possibly substitution derivatives of

$$Al_4(SiO_4)_3 = \overset{I}{R}_3Al_3(SiO_4)_3,\ \overset{I}{R}_6Al_2(SiO_4)_3,\ \overset{I}{R}_9Al(SiO_4)_3$$

$$\text{or } \overset{I}{R}\overset{II}{R}Al_3(SiO_4)_3, \text{ etc.,}$$

and possibly also to some extent in the more siliceous varieties derivatives of $Al_4(Si_3O_8)_3$.

$\overset{I}{R}$ = H, K, Na, Li, or (MgF), (AlF_2), (AlO).

$\overset{II}{R}$ = Mg, Fe, Mn.

Al may be replaced by Fe and Cr.

Muscovite, $H_2KAl_3(SiO_4)_3$.

Paragonite, $H_2NaAl_3(SiO_4)_3$.

Lepidolite, $KLi[Al(OH,F)_2]Al(SiO_3)_3$ pt.

Zinnwaldite, $(K,Li)_3FeAl_3Si_5O_{16}(OH,F)_2$, ?

Phlogopite, $H,K,(MgF)_3Mg_3Al(SiO_4)_2$.

Biotite, $(H,K)_2(Mg,Fe)_2(Al,Fe)_2(SiO_4)_3$ pt.

Lepidomelane, a variety of biotite rich in ferric iron.

Monoclinic, prismatic class.

In muscovite $a:b:c = 0.57735:1:3.3128$, $\beta = 89° 54'$.

Biotite $a:b:c = 0.57735:1:3.2743$, $\beta = 90° 0'$.

Approximating in symmetry the orthorhombic or trigonal (rhombohedral) systems. The edges of the basal pinacoid (001) are always at 60° or 120°.

Twinning plane is one perpendicular to (001) in the zone of the left-hand or right-hand prism plane ($1\bar{1}0$) or (110). The composition plane is commonly the basal pinacoid (001). Sometimes the twinning plane is also the composition plane. Rarely the twinning plane, at right angles to (001), is in the zone of (001) (130), the composition plane being (001).

Cleavage: highly perfect parallel to (001), producing thin, elastic laminæ. Parting parallel to (010) and ($\bar{1}11$) and other planes less definitely determined ($\bar{1}12$, 111, 114), shown in the percussion figure. Also gliding planes parallel to ($\bar{2}05$), (135), and ($\bar{1}04$), perhaps (104), as shown in the pressure figure. Fracture seldom produced. H. = 2–2.5 muscovite; 2.5–3 biotite, paragonite; 2.5–4 lepidolite. Sp.gr. = 2.7–3.2.

Optical Properties. The acute bisectrix X is nearly normal to (001) in all cases. The plane of the optic axes is at right angles to the second pinacoid (010) in muscovite, paragonite, lepidolite, and in some varieties of biotite called anomite. It is parallel to (010) in zinnwaldite, phlogopite, lepidomelane, and most biotite. The angle between the optic axes, $2V$, is almost 0° in some biotites, and is generally small in others, but may be large in rare instances. It is somewhat larger in phlogopite, and is commonly large in muscovite, paragonite, and lepidolite, $2E$ ranging from 50° to 70° in most cases.

The refraction ranges from $\alpha = 1.5412$, $\gamma = 1.5745$ to $\alpha = 1.5795$, $\gamma = 1.638$, and the double refraction from $\gamma - \alpha = 0.033$ to 0.058.

Color: colorless, white, gray, greenish to strong green, yellowish to brown, violet, lilac to rose-red, reddish brown, black. The same colors appear in thin sections. The more strongly colored varieties exhibit marked pleochroism and absorption. Luster vitreous to pearly or silky. In the darker-colored varieties the luster is sometimes splendent to submetallic. Streak uncolored.

Chemical Composition.—The micas are silicates, in most cases orthosilicates, of aluminium, potassium, and hydrogen, generally with magnesium and ferrous iron; in some varieties there is ferric iron, rarely chromium; in others sodium or lithium, rarely rubidium and cæsium, also barium and manganese. Fluorine and titanium are present in some varieties.

According to Clarke the micas may be considered as substitution derivatives of $Al_4(SiO_4)_3$, with which may be combined in the more siliceous micas $Al_4(Si_3O_8)_3$. All the variations may be expressed by combinations of $\overset{\text{I}}{R}_3Al_3(SiO_4)_3$ and $\overset{\text{I}}{R}_9Al(SiO_4)_3$, together with $\overset{\text{I}}{R}_3Al_3(Si_3O_8)_3$ and $\overset{\text{I}}{R}_9Al(Si_3O_8)_3$. $\overset{\text{I}}{R}_2$ may be replaced by $\overset{\text{II}}{R}$, and Al by $\overset{\text{III}}{Fe}$ and $\overset{\text{III}}{Cr}$. $\overset{\text{I}}{R}$ represents H, K, Na, Li, or a univalent radical,

CHEMICAL ANALYSES OF MICAS.

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	Li_2O	H_2O	F	
Theoretical Muscovite, $H_2KAl_3(SiO_4)_3$	45.2	38.5	—	—	—	—	—	11.8	—	4.5	—	=100.00
1. Muscovite, Bengal	45.57	36.72	0.95	1.28	0.38	0.21	0.62	8.81	0.19	5.05	0.15	= 99.93
2. " East Indies	45.71	36.57	1.19	1.07	0.71	0.46	0.79	9.22	—	4.83	0.12	=100.67
3. " Schüttenhofen	43.67	36.70	2.10	0.55	—	—	1.95	8.57[a]	tr.	5.50[b]	0.35	= 99.39
4. " S. Royalston	45.97	30.40	5.11	1.05	2.03	—	0.59	9.92	—	4.00	0.74	= 99.81
5. " Haddam, Conn.	45.05	30.57	1.14	1.73	0.97	—	2.13	10.23	—	6.19	1.26	= 99.27
6. " Monroe, Conn.	46.50	33.91	2.69	—	0.90	—	2.70	7.32	—	4.63	0.82	Cl 0.31 = 99.78
7. Chrome mica, Sisersk	46.17	29.71	2.03	—	2.28	—	—	10.40	—	5.42	—	Cr_2O_3 3.51 = 99.52
8. " " Montgomery County, Md.	42.21	34.55	1.03	—	3.13	0.47	0.82	9.16	—	6.77	—	Cr_2O_3 2.03 =100.17
Theoretical Paragonite, $H_2NaAl_3(SiO_4)_3$	47.1	40.1	—	—	—	—	8.1	—	—	4.7	—	=100.00
9. Paragonite, Mte. Campione	46.81	40.06	tr.	—	0.65	1.26	6.40	tr.	—	4.82	—	=100.00
10. " Prägraten	44.65	40.41	—	0.84	0.37	0.52	7.06	1.71	—	5.04	—	Cr_3O_2 0.10 =100.70
11. Leipdolite, Schüttenhofen	49.25	25.27	—	0.84	—	—	0.35	13.85[c]	5.38	1.76	5.68	SnO_2 0.06 MnO 0.85 =103.29
12. " (foliated), Paris, Me.	50.92	24.99	0.30	0.23	tr.	—	2.11	11.38	4.20	1.96	6.29	=102.38

[a] Incl. Rb, Cs. [b] Below 300° 1.15. [c] Incl. Rb, Cs.

CHEMICAL ANALYSES OF MICAS—*Continued.*

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	Li_2O	H_2O	F	
13. Polylithionite, Kangerdluarsuk	59.25	12.57	—	0.93	—	—	7.63	5.37	9.04	—	7.52	=102.11
14. Zinnwaldite, Zinnwald	43.44	21.84	1.41	10.06	—	—	0.54	10.58	3.36	—	7.62	MnO 1.89 =103.74
15. Cryophyllite, Cape Ann, Mass.	51.96	16.89	2.63	6.32	0.15		0.87	10.70	4.87	1.31	6.78	MnO 0.24 =102.72
16. Phlogopite, Pargas	43.43	13.76	0.16	1.35	27.20	—	1.30	8.06	—	0.92	4.21	=100.39
17. " Burgess, Ont.	39.66	17.00	0.27	0.20	26.49	—	0.60	9.97	—	2.99	2.24	BaO 0.62 TiO_2 0.56=100.60
18. " Edwards	44.81	10.87	—	0.31	28.90	—	0.38	8.40	0.08	5.42	—	Ign 100°0.96 =100.13
19. " (white), De Kalb	41.68	13.21	0.16	0.11	28.16	—	1.04	8.78	—	3.10	3.07	BaO 2.08 TiO_2 0.38=101.77
20. " (black), Rossie	40.63	13.04	1.12	7.62	21.47	—	0.57	10.14	—	2.47	4.00	BaO 0.04 TiO_2 1.16=102.26
21. " Leucite Hills, Wyo.	42.56	12.18	2.73	0.90	22.40	0.20	0.44	10.70	—	2.35	2.46	TiO_2 2.09 P_2O_5 0.06, Cr_2O_3 0.73, BaO 1.00, SrO tr.=100.80
22. " Horberig, Oberbergen	36.42	17.92	2.83	7.04	20.52	—	2.60	6.54	—	2.50	—	TiO_2 3.99 =100.36
23. Biotite, Lake Baikal	40.00	17.28	0.72	4.88	23.91	—	1.47	8.57	—	1.37	1.57	= 99.77
24. " Greenwood Furnace	40.81	16.47	2.16	5.92	21.08	—	1.55	9.01	—	2.19	tr.	= 99.19
25. " black, Miask	32.49	12.34	6.56	25.13	5.29	—	0.88	9.59	—	2.42	1.61	TiO_2 4.03 =100.34
26. " Miask	33.24	14.90	5.92	23.57	5.15	0.40	1.45	7.77	—	2.19	—	0.95 4.73 MO 0.95, TiO_2 4.73 =100.27
27. " Pike's Peak	34.21	16.53	20.15	14.17	1.34	0.48	1.43	6.50	—	4.54	0.08	MnO 0.91 =100.34

CHEMICAL ANALYSES OF MICAS—*Continued.*

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	Li_2O	H_2O	F	MnO	TiO_2
28. Biotite, El Capitan, Yosemite, Cal.	36.02	18.81	5.60	14.75	9.82	0.65	0.38	9.32	—	2.57	0.26	0.80	1.13
										BaO tr., SrO none = 100.11			
29. " Nevada Falls Trail, Yosemite, Cal.	35.75	14.70	4.65	14.08	12.37	0.17	0.32	9.19	—	4.67	0.17	0.45	3.16
										P_2O_5 0.03 Cr_2O_3 tr., NiO 0.02, BaO 0.12, SrO(?), ZrO_2 none, V_2O_3 0.05 = 99.90			
30. " Butte, Mont.	35.79	13.70	5.22	13.72	12.13	0.05	0.15	9.09	—	4.85	0.76	0.19	3.51
										P_2O_5 0.10, Cl 0.20, BaO 0.13, SrO none = 99.59			
31. " Alpine County Cal.	35.62	15.24	4.69	13.67	12.70	0.95	0.50	7.72	—	5.30	—	0.74	2.61
										P_2O_5 none, SrO tr. = 100.00			
32. " pyroxene-gneiss, north fork, Mokelumne River, Cal.	36.62	14.37	4.04	17.09	9.68	1.48	0.45	8.20	tr.	4.16	0.10	0.40	3.03
										P_2O_5 none, BaO 0.33, SrO tr. = 99.95			
33. Lepidomelane, Brevik	32.97	11.88	16.48	20.72	1.08	—	0.30	8.03	—	3.35	1.29	3.64	2.42
												= 102.16	
34. " Langesund fjord	34.37	6.84	24.89	7.47	4.05	0.78	2.13	9.03	—	2.27	—	2.41	4.68
												= 98.92	
35. " Litchfield, Me.	32.09	18.52	19.49	14.10	1.01	—	1.55	8.12	—	4.62	—	1.42	—
												= 100.92	
36. " Baltimore	35.78	16.39	14.55	11.02	8.67	—	0.56	7.76	—	4.48	—	1.08	—
												= 100.29	
37. " (annite), Cape Ann, Mass.	31.96	11.93	8.06	30.35	0.05	0.23	1.54	8.46	—	4.25	—	0.21	3.42
												= 100.46	

as MgF, AlF_2, AlO. $\overset{II}{R}$ represents Mg, Fe, Mn, etc. In this way the presence of fluorine and of an excess of oxygen is accounted for.

According to Tschermak the micas consist of isomorphous mixtures of the hypothetical molecules; **K** = $H_2KAl_3Si_3O_{12}$, **M** = $Mg_6Si_3O_{12}$, **S** = $H_4Si_5O_{12}$. The first corresponds to ordinary muscovite; the second to olivine (forsterite); the third is a hypothetical silicon hydroxide, which may be replaced by $Si_5F_{12}O_4$. The ratio between H and K may vary, and other univalent metals may replace them. Other metals may replace Al, Mg, and Si.

Muscovite is commonly an orthosilicate of aluminium, hydrogen, and potassium, $H_2KAl_3(SiO_4)_3$, conforming to $R_3Al_3(SiO_4)_3$ or to Tschermak's molecule **K**. But the ratio of H to K generally varies from that of 2:1. There may be a small amount of iron present, rarely barium, and chromium in certain varieties, fuchsite, etc. The more siliceous muscovites, called phengite, may be regarded as mixtures of $H_2KAl_3(SiO_4)_3$ and $H_2KAl_3(Si_3O_8)_3$, or, according to Tschermak, $3\mathbf{K}+\mathbf{S}$, $3H_2KAl_3Si_3O_{12}+H_4Si_5O_{12}$. The chemical composition of muscovites from various localities shown in analyses 1 to 6 indicates their variation from the hypothetical molecule. The composition of two chromium-micas is given in analyses 7 and 8.

Paragonite is a sodium-mica corresponding to muscovite in composition. Analyses 9 and 10 show a close approach to the theoretical composition.

Lepidolite in some varieties may be considered a metasilicate or a mixture of $\overset{I}{R}_6Al_2(SiO_4)_3+\overset{I}{R}_6Al_2(Si_3O_8)_3$, or more specifically $HKLiAl_3(SiO_4)_3+K_3Li_3(AlFe_2)_3Al(Si_3O_8)_3$. It is characterized by notable amounts of lithium and fluorine, and sometimes small amounts of rubidium and cæsium: analyses 11 and 12.

Polylithionite is a variety high in lithium and sodium, with little or no iron: analysis 13.

Zinnwaldite is a lithium-mica with a notable amount of iron: analysis 14. *Cryophyllite* is similar, but with somewhat different proportions: analysis 15.

Phlogopite is a magnesium-mica, rich in potassium, with variable amounts of fluorine and hydrogen. It contains little iron. Typical phlogopite, according to Clarke, is $\overset{I}{R}_3Mg_3Al(SiO_4)_3$, where $\overset{I}{R}$ = H, K, MgF. Analysis 18 is nearly equivalent to $H_6K_2Mg_7Al_2(SiO_4)_7$. Other phlogopites are represented by analyses 16, 17, 19, 20, 21.

Biotite is iron-magnesium-mica rich in potassium, often with notable amount of titanium and varying considerably in the pro-

portions of iron and magnesium. Ordinary biotite is nearly $(H,K)_2(Mg,Fe)_2Al_2(SiO_4)_3$ or $(H,K)_2Al_2(SiO_4)_2+(Mg,Fe)_2(SiO_4)$. It ranges chiefly from this to $(H,K)_2(Mg,Fe)_4(Al,Fe)_2(SiO_4)_4$. The variations in composition are shown in part by analyses 23 to 32. Analysis 22 is that of a variety intermediate between phlogopite and biotite.

Lepidomelane may be considered a variety of biotite rich in iron, both ferrous and ferric, with little magnesium: analyses 33 to 37. It is in some varieties an orthosilicate, in others it is more basic.

Alterations.—The micas behave differently towards chemical reagents according to their composition, and in like manner they appear to be quite differently susceptible to the forces of decomposition encountered in nature. Muscovite and paragonite are not decomposed by acids, lepidolite and zinnwaldite are attacked but not completely decomposed by the common acids. Phlogopite and biotite are completely decomposed by sulphuric acid, leaving the silica in thin scales. Lepidomelane is easily decomposed by hydrochloric acid, depositing silica in scales. From this it is seen that the purely alkalic micas are least affected by acids, the magnesium micas are more susceptible, while the strongly ferric micas are readily decomposed by hydrochloric acid. In the study of rocks the decomposition of muscovite and the other purely alkalic micas has seldom been noted; muscovite is frequently an alteration product of other minerals and therefore stable under ordinary conditions. It is known, however, to become hydrated in some cases, losing potassium and taking up magnesium, calcium, or sodium, and may alter into steatite and serpentine, or to some form of vermiculite. Alteration products of the other purely alkalic micas are not mentioned in the text-books.

Phlogopite alters at times to steatite and serpentine and also to a number of different vermiculites. The alteration to talc results in an aggregation of fibrous scaly particles. In some cases rutile is also produced.

Biotite alters in several ways. It may change in color from brown to green while still retaining its mica character, the optical constants changing with the chemical change. The commonest alteration is to chlorite or vermiculite-like minerals, often retaining the micaceous cleavage and changing into parallelly oriented chlorite. Or it may pass into a confused aggregation of minute scales of chlorite, with the accompaniment of epidote and rutile or cassiterite, iron oxides, carbonates, and quartz. Often alteration is accompanied

by the deposition of lenticular aggregates of carbonates between the cleavage laminæ of the mica.

In certain lavas and porphyritic rocks biotite crystals have undergone a decomposition and recrystallization into magnetite and pyroxene prior to the final consolidation of the rock magma in the same manner as in the case of some hornblendes. The biotite molecule appears to have become unstable and to have melted and crystallized into minerals without hydrogen. Besides magnetite and pyroxene it is evident potash-feldspar or feldspathic molecules or potash-mica must be liberated to crystallize with the magnetite and pyroxene or be taken up by the surrounding groundmass. The process may have been checked in various stages, leaving in some cases a rim or margin filled with magnetite, in others affecting the whole mica crystal. This form of alteration is oftener observed in holocrystalline porphyries than in glassy ones.

Crystal Forms.—The micas are isomorphous compounds crystallizing in the monoclinic system, prismatic class. Adopting the orientation chosen by Tschermak, the axial ratios are: muscovite, $a:b:c=0.57735:1:3.3128$, $\beta=89°\,54'$; biotite, $a:b:c=0.57735:1:3.2743$, $\beta=90°\,0'$. The symmetry in some cases approaches orthorhombic, in others trigonal (rhombohedral). The angles between the edges of the basal plane (001) are 60° or 120°, so that tabular crystals have rhombic or hexagonal outlines.

The habit of the crystals is commonly tabular parallel to (001), in some cases thin, in others thick, grading into tapering prismatic shapes, with sides more or less rough and striated parallel to the trace of (001). Tabular crystals are in some instances equidimensional and hexagonal; in others rhombic with the acute angles truncated by (010) or a prism of the first kind; in others elongated parallel to the axis a. The crystal forms commonly developed are $c(001)$, $b(010)$, $M(221)$ with $e(023)$ and $\mu(\bar{1}11)$ in muscovite, Figs. 1 and 3, and in addition $o(112)$, $z(132)$ and $r(\bar{1}01)$ in biotite, Figs. 2 and 4.

Mica occurs in isolated crystals scattered through rock masses and on the walls of cavities, and also in groups of crystals, in some cases in curved, more or less spherical aggregations, in others in radiating fan-like clusters. It also occurs in dense aggregations of variously oriented crystals, sometimes of microscopic dimensions.

Euhedral crystals develop as phenocrysts in porphyries, and as microscopic crystals in volcanic glasses. They occur to a less extent in metamorphic rocks, such as crystalline limestones. Subhedral

and anhedral crystals are common in the more crystalline igneous and metamorphic rocks.

Twinning is common with twins in contact on the basal pinacoid (001), the twinning plane being perpendicular to (001) and situated

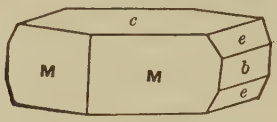


FIG. 1.

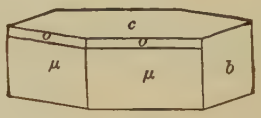


FIG. 2.

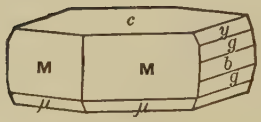


FIG. 3.

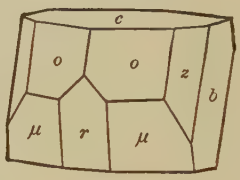


FIG. 4.

in the zone (001)(110), Fig. 5, or the zone (001)(110), Fig. 6. In some cases the twinned parts elongated parallel to the *a* axis cross one another as in Fig. 7.

This form of twinning is recognized in cross sections by the different optical orientation of the twinned parts when the acute bisectrix *X* is inclined to the normal to (001). Less frequently the twins are in

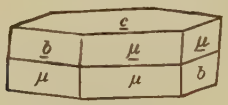


FIG. 5.

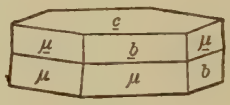
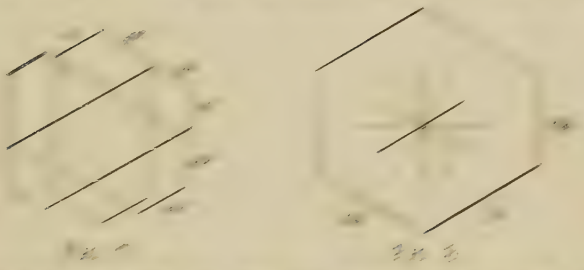


FIG. 6.

contact on the twinning plane. In another mode of twinning the twinning plane is perpendicular to (001) in the zone (001)(130), and the composition plane is (001).

Cleavage.—Highly perfect parallel to (001), causing the crystals to cleave in extremely thin elastic laminæ. In thin sections of mica in rocks, when cut parallel to (001), no cleavage lines or fracture cracks of any kind are commonly visible. In all other positions of the section numerous parallel, sharply defined, cleavage cracks are noticeable in the direction of the trace of (001). In most instances there are no other cracks of cleavage, parting, or fracture developed in the mica in rock sections.

Other lines of parting may be developed in mica by means of pressure, and others by a sudden blow with a sharp-pointed instru-



[illegible]

Optical Properties.—The micas are biaxial with a noticeable angle between the optic axes in most varieties, but in some biotites the angle is so small as not to be seen by ordinary observation, so that they appear like uniaxial crystals. The acute bisectrix in all varieties is X, and is nearly normal to the plane of cleavage (001), rarely varying as much as 5° from the normal to this plane. All micas are optically negative (−). The plane of the optic axes in some micas is at right angles to the plane of symmetry (010). These are called micas of the *first class*, Fig. 9, and include muscovite, paragonite, most lepidolites, and some biotites called anomites for this reason. In other micas the plane of the optic axes lies in the

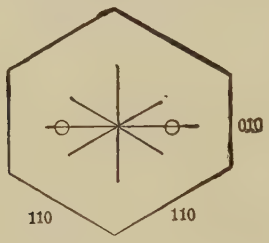


FIG. 9.

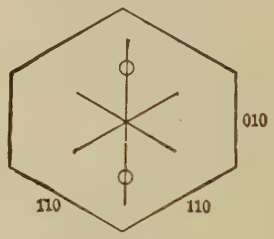


FIG. 10.

plane of symmetry (010). These form the *second class*, Fig. 10; and include zinnwaldite, phlogopite, lepidomelane, and most biotites.

The angle between the optic axes is almost 0° in some biotites. $2E$ varies from this to 10° or 12° in most varieties, and reaches 60° and 70° in exceptional biotites. It has a small value in phlogopite. In all varieties of purely alkalic micas $2E$ is commonly large, mostly from 60° to 80°. But in some muscovite it is quite small, even 0°. The accompanying table shows the variations in $2E$ and in the angle of inclination of the bisectrix X to the normal to (001).

Muscovite:		$2E$	
Violet-gray	New York Island	56° 20′–56° 40′	Silliman
Dark brown	Royalston, Mass.	57° 30′–59°	"
Greenish gray	Philadelphia, Pa.	60° 30′–61°	"
Brown	Monroe, Conn.	64° 30′–65° 30′	"
Violet-brown	Royalston, Mass.	65°	"
Blackish gray	Jones Falls, Baltimore	66° 15′–66° 30′	"
Greenish gray (granite)	Acworth, N. H.	67° 15′–67° 30′	"
Dark brown	Royalston, Mass.	69° 40′–70°	"
Greenish yellow	Goshen, Mass.	70° –70° 30′	"
Light brown, transparent	Hebron, Me.	71° 40′–71° 50′	"
Yellowish brown	Paris, Me.	72° 15′–72° 30′	"
Gray	Orange, N. H.	73° –74°	"
Pink	Lenox, Mass.	75° –75° 30′	"

A similar range of angles has been found by Senarmont, Grailich, Bauer.

	$X \wedge \perp (001)$	$2E$		
Muscovite, Abühl	$+1° 44'–1° 41'$	$62° 46'_y$		Tschermak
Bengal	$+1° 41'–1° 40'$	$68° 54'_y$		"
East Indies	$+0° 30'–0° 31'$	$71° 54'$	$2V = 43° 48'.8_y$	"
Ural Mts.	$1° 42'$	$64° 14'$	$2V = 40° 21'$	Bauer
Lepidolite, Schüttenhofen	$1° 33\frac{1}{2}'_y$	$84° 1'_y$		Scharizer
Siberia		$73° 2'$		"
Wolkenburg, Saxony		$57° 10'$		"
Haddam, Conn.		$76° 51'$		Tschermak
Massachusetts		$76° 10'–76° 40'$		Grailich
Whitish green, Paris, Me.		$74° –74° 30'$		Silliman
Elba		$72° –50°$		Tschermak
Pink, Penig, Saxony		$59° 24'$		Bauer
More strongly colored, Penig, Saxony		$36°–32°$		"
Paragonite	$0°$ approx.	$70°$ approx.		
Zinnwaldite:				
Pale greenish, Kangerdluarsuk	$5'–8'$	$67° 19'$		Lorenzen
Pale violet, Siberia	$+4° 2'$	$65° 19'$		Tschermak
Zinnwald	$+1° 4'$	$50° 25'$		"
Cryophyllite, Rockport, Mass.		$56°$		"
Rabenglimmer, Altenberg		Small to $0°$		
Chromium mica, Ural		$68° 35'_y$		Arzruni
" " Montgomery Co., Md.		$68° 16'_y$		Gill
" " Ouro Preto		$69°–70°$	$\rho > v$	Des Cloizeaux
Biotite:				
Yellow, Vesuvius	$+0° 32'_y$	$6° 24'_y$		Tschermak
Dark green, "	$+0° 27'_y$	$12° 48'_y$		"
Deep brown, "	$+0° 9'_y$	$10° 23'_y$		"
Brown, "	$-0° 43'_y$	$8° 10'_y$		"
Various localities		$0°–5°$		Grailich
Various U. S. localities		$7°–18°$		Silliman
Black, Siberia		$20°_y$		Tschermak
Dark brown, Vesuvius		$37° 30'_y$		"
Black, Albanian Hills		$56°_y$		"
Red-brown, Katzenbuckel		$8° 40'–62°$		Lattermann
Repistye Schemnitz	$3° 15'$	$72° 30'$		"
Vulcano	$3° 30'$	—		"
Ditro	$5°$	—		"
Azores	$4°$	—		Mügge
Anomite:				
Red-brown. Dürnstein		$18° 54'$		Becke
" " Alnö		$8° –10°$		Eichstädt
Tomback-brown, "		$0°–25°$	$\rho < v$	Lattermann
Michaelstein		$10°–22°$	"	"

	$X \wedge \perp(001)$	$2E$		
Anomite, Repistye, Schemnitz		10°–40°	$\rho < v$	Lattermann
" Katzenbuckel		40° approx.	"	"
" One crystal, L. Baikal		$\left\{\begin{matrix}16°\ 0'_r \\ 12°\ 44'_r\end{matrix}\right\}$		Tschermak
Phlogopite, Ceylon { light		15°		Lacroix
Ceylon { dark		35°		Lacroix
" Leucite Hills, Wyo.	3°	35° approx.		Cross
" Natural Bridge, N. Y.	+1° 19'$_r$	—		Tschermak
" Burgess, Ont.	+0° 24'$_r$	—		"

In the alkalic micas the dispersion of the optic axes is $\rho > v$; in biotite it is in some cases $\rho < v$, in others $\rho > v$. Des Cloizeaux has found that the angle between the optic axes in muscovite decreases with increase of temperature.

	6.6°	47°	71.5°	95.5°	120°	155.8° C.
Silver, white, Algiers $2E_r$ =	70° 4′	69° 42′	69° 32′	69° 29′	69° 22′	68° 56′
					121°	146.5° 185.5° C
Colorless, New Hampshire $2E_r$ =	69° 44′	69° 32′	69° 4′	68° 56′	68° 38′	68° 17′ 68° 5′
						170.8° C.
Light red, Goshen, Mass. $2E_r$ =	76° 50′	76° 24′	76° 16′	76° 7′	75° 50′	75° 30′ 75° 10′

INDICES OF REFRACTION OF MICA.

	α	β	γ	$\gamma-\alpha$	
Muscovite, East Indies	1.5609_y	1.5941_y	1.5997_y	$.0388_y$	Kohlrausch
" ?	1.5692_y	1.6049_y	1.6117_y	$.0425_y$	Matthiessen
" ?	1.5601_y	1.5936_y	1.5977_y	$.0376_y$	Pulfrich
" ?	1.5573	1.5866	1.5904	.0331	Hecht
" Monte Orfano	1.5619_y	1.5947_y	1.6027_y	$.0408_y$	Viola
" Oberes Veltlin	1.560	1.593	1.609	.0490	Link
" Vendée	1.5601	—	1.5963	.0362	Wallérant
Lepidolite, Schüttenhofen, Bohemia	—	1.5975	1.6047	—	Scharizer
Biotite, Oberes Veltlin(?)	1.504	1.589	1.589	.0850	Link
" yellowish brown, Vesuvius	1.5412_y	—	1.5745	$.0333_y$	Kohlrausch
" light green, Mte. Somma	1.5443	—	1.5792	.0349	Zimanyi
" olive-green, Rocca di Papa	1.5618	—	1.6032	.0414	"
" black, Mte. Somma	1.5795	—	1.638	.0585	"
" black, Teplitz	1.5829	—	—	—	"
" black, —	1.586	—	—	—	Kohlrausch
Phlogopite, Templeton	1.562	1.606	1.606	.0440	Lévy–Lacroix

The refraction of mica ranges from that of quartz to that of amphibole, as seen in the accompanying table of indices, which vary considerably for each kind of mica so far as studied. The

refraction for biotite increases in the darker-colored varieties, presumably with the percentage of iron, the double refraction increasing in the same manner. The double refraction is strong for all kinds of mica from 0.033 to 0.058, but is more noticeable in thin sections of colorless and light-colored varieties than in those of dark-colored mica. In thin sections 0.03 mm. thick the interference colors reach those of the second and third order. Sections parallel to the cleavage plane (001) are nearly parallel to the plane of Y and Z, and since $\gamma-\beta$ is always small the interference color exhibited by such sections is always low, usually gray in muscovite, and darkness in the case of most biotites. Thin sections of mica noticeably inclined to (001) exhibit numerous cleavage cracks and strong double refraction; those parallel to (001) show no cleavage cracks, very low double refraction, and an interference figure in convergent light.

Color.—Micas have a wide range of color, the purely alkalic varieties being colorless to light shades of various colors, the iron-magnesian micas browns, greens, and black, less often red.

Muscovite may be colorless, white, gray, yellow, brown, pale green to olive-green, violet, rarely rose-red. *Paragonite* may be yellowish, grayish, greenish, light apple-green. *Lepidolite* is white, yellowish, grayish, lilac, rose-red. Zinnwaldite has the same colors as lepidolite, but may also be brown. *Phlogopite* is oftener yellowish brown or brownish red, but may also be pale brownish yellow, green, white, colorless. *Biotite* is usually green or brown to black, less often pale yellow, and rarely white. *Lepidomelane* is black.

In thin section the lighter-colored micas are colorless or nearly so; the strongly colored and black micas are lighter-colored and strongly pleochroic. In nearly all cases the rays vibrating parallel to Y and Z are strongly colored or strongly absorbed; those vibrating parallel to X are much lighter-colored or little absorbed. The absorption is commonly $Z=Y>X$. Thus in sections cut parallel to (001), and nearly so to Y and Z, there is the strongest color with little or no pleochroism, while in sections inclined or perpendicular to (001) there is pronounced pleochroism, the rays vibrating parallel to the cleavage cracks being strongly colored or showing strong absorption, those vibrating at right angles to the cleavage being lighter-colored. Usually the variation exhibited in one section is between different tones of the same dominant color, or different shades of the same color. Less often the contrasted colors are distinctly different, as red and green, or blue and green. The following are some of the colors commonly seen in thin sections:

Muscovite: colorless, exhibits absorption without pleochroism.

Chromium-mica, Maryland: X robin's-egg blue; Y yellowish green; Z bluish chrome-green.

Zinnwaldite: colorless, light yellowish to deep red-brown.
X colorless, Y and Z brownish gray.
X yellow-brown, Y and Z dark-brown to reddish.
$Z>Y>X$.

Paragonite, lepidolite: colorless. Cryophyllite, Rockport, Mass.: X emerald-green, Y and Z brownish red.

Phlogopite: colorless, to pale yellow, to light brown in that from Leucite Hills, Wyo. X pale yellow, Y and Z salmon-pink. $Z>Y>X$.

Biotite: X light yellow, Y and Z deep brown to black.
X red, Y and Z red brown to black.
X light green, Y and Z deep green to black.
$Z>Y>X$ or $Y>Z>X$.

Lepidomelane (?): always brown or sometimes green (?).

Luster.—The luster of micas is often different on the cleavage plane from what it is on the other planes. It is vitreous to pearly, sometimes submetallic in the black varieties. On the edges of tabular crystals it is sometimes glassy, often dull.

Zonal structure is sometimes present in micas, as well as parallel growth. They are produced by changes in the composition of the mica during the period of crystallization. Usually the more alkalic variety surrounds the more ferro-magnesian variety. Thus muscovite or paragonite incloses biotite or phlogopite. Lepidolite often surrounds muscovite. The outside mica in some cases completely surrounds the inner, both on the basal plane and the marginal planes, enclosing it as a shell. In other cases it surrounds it only on the margin, or only on the basal planes $(001)(00\bar{1})$.

Inclusions in micas are in part characteristic of certain occurrences, in part chance inclosures of associated minerals. The alkalic micas are generally quite free from inclusions, though they may contain crystals of tourmaline, garnet, etc. Zinnwaldite, phlogopite, and biotite often contain great numbers. Zinnwaldite occurring in tin-bearing granites frequently incloses crystals of cassiterite, topaz, zircon, and rutile, surrounding which there are frequently darker-colored, pleochoric areas of mica, which in cross section appear as halos or aureoles.

Phlogopite is sometimes filled with minute crystals of rutile and

other minerals arranged in lines intersecting one another at angles of 60°, parallel to the traces of (001) and (110) on the basal plane. In some cases they are parallel to lines bisecting these directions. This produces the so-called asterism seen in transmitted light. There are often inclusions of quartz and garnet in extremely thin films between the mica laminæ; also crystals of iron oxide, hematite, and magnetite, in clusters and dendritic forms, so extremely thin as to transmit light, the hematite being red and the magnetite brown. Tourmaline occurs in scattered crystals, or in prisms arranged in three directions in the basal plane parallel to the traces of (001)(110), or they may be in radiating clusters.

Biotite in igneous rocks usually incloses crystals of iron oxide, apatite, and zircon, and occasionally fluid inclusions, which are generally destroyed in the preparation of thin sections, but may be observed in isolated crystals. Glass inclusions seldom if ever occur. Rutile needles and sagenite-webs are common in biotite in certain kinds of rocks. In some instances they are clearly primary crystallizations; in others they are undoubtedly secondary.

Biotite is frequently intergrown with hornblende and pyroxene, so that they mutually inclose one another, having grown at the same time. In some igneous rocks biotite incloses many small crystals of the minerals associated with it in a poikilitic manner, acting as a matrix for them. This is especially the case in some mica-peridotites.

Modes of Occurrence.—The commoner micas, muscovite and biotite, occur abundantly in both igneous and metamorphic rocks and are capable of crystallizing from igneous magmas or from aqueous solutions. Others are oftener met with in one or the other of these categories of rocks, or are known only in one mode of occurrence.

Muscovite is a pyrogenetic mineral in certain kinds of igneous rocks, being a primary constituent of the more crystalline rocks rich in alumina and potash and poor in iron and magnesia. It is oftenest developed in certain granites and granitic pegmatites, also in some syenites, nephelite-syenites, and in their pegmatites. It is not a primary constituent of the lavas and glassy forms of these magmas. Muscovite is abundant in the metamorphic rocks, especially the mica-schists, when it is often accompanied by biotite. It also occurs in gneiss and allied rocks, and is common in various phases of contact metamorphism of rocks of widely different types. It may be a secondary mineral, often called sericite, in any kind of rock, resulting from the alteration of aluminous alkalic minerals, such as the feldspars and feldspathoids, and also other micas.

Its many modifications of aggregation and modes of occurrence have received special names, which are found in petrography and mineralogy. Of these the commoner are: *Sericite*, an aggregation of microscopic crystals with anhedral shapes, usually in scale-like plates, either in diverse positions or in clusters of curved or radiating scales. It has a silky luster. *Damourite*, a somewhat less elastic variety with a pearly to silky luster and unctuous feeling. *Margarodite* is much the same; the name was given to a talc-like mica from Mt. Greiner in the Zillerthal. *Fuchsite* is a chromium-muscovite, the original mineral also from the Zillerthal. There are numerous ill-defined aggregations resulting from the alteration of aluminous alkalic minerals which approach muscovite closely in composition and may be referred to here. *Pinite*, a brown pseudomorph after cordierite; *pinitoid*, a greenish pseudomorph after feldspar in a granite porphyry and in other rocks; *hydrophilite*, much the same, occurs in gneiss; *liebenerite*, an alteration product of feldspar in a porphyry, from the Fleimsthal; *gieseckite*, a pseudomorph after nephelite; and others.

Paragonite occurs in crystalline schists and is not known as a pyrogenetic mineral. It forms a schist at Mte. Campione, Switzerland, carrying cyanite and staurolite, also garnet and tourmaline. In the Pfitschthal and Zillerthal it is dense and compact like soapstone and contains actinolite. It is known in a number of other localities, but is not of common occurrence in the metamorphic rocks, and appears to be the rarest variety of mica.

Lepidolite occurs in granite and pegmatite. It is best known in pegmatites, where it forms violet or lilac-tinted crystals associated with muscovite. It also forms granular rock masses, as in the vicinity of San Diego, Cal., where it forms the matrix for the well-known crystals of rubellite. It is commonly accompanied by tourmaline, spodumene, amblygonite, topaz, and other minerals.

Zinnwaldite occurs chiefly in tin-bearing granites at Zinnwald in the Erzgebirge, in Cornwall, and elsewhere. *Cryophyllite* is found in the granite at Rockport, Mass. *Polylithionite* occurs in the nephelite-syenite at Kangerdluarsuk, Greenland.

Phlogopite is chiefly found in metamorphosed limestones, and dolomites in the crystalline schists, and in zones of contact metamorphism. It is also found in serpentine. It occurs as a pyrogenetic mineral in some igneous rocks rich in magnesia and poor in iron, as in certain peridotites, and in the leucitic lavas of Leucite Hills, Wyo., but is much less common than biotite.

Biotite occurs in igneous and in metamorphic rocks. It crystallizes in a great variety of rock magmas, developing in coarse-grained as well as in aphanitic and glassy rocks. It occurs in many granites, diorites, gabbros, syenites, nephelite-syenites, peridotites, and rocks closely related to them. But it is oftener developed in the phanerocrystalline than in the aphanitic or glassy equivalents of a given magma. It is rare in rock with little magnesia or little potash. In metamorphic rock it is a common constituent in gneisses and schists, and is frequently developed in zones of contact metamorphism.

While most of the biotite belongs to mica of the second class and has been called *meroxene*, a very considerable part has the plane of the optic axes at right angles to the plane of symmetry and is *anomite*. But it has not been found that this optical property is connected with a particular chemical composition of the mica, or of the rock magma, nor with the mode of occurrence. Biotites of both kinds have been found in the same rocks. There appears to be no more occasion for discriminating between these two optical varieties of biotite than for emphasizing the difference between the optically similar variations in potash-feldspar.

Lepidomelane is known chiefly in feldspathic igneous rocks relatively low in magnesia with notable amounts of iron oxide, as in certain granites, syenites, and nephelite-syenites, where it is often associated with ægirite or soda-amphibole. It occurs in the nephelite-syenites of the Langesund fjord, Norway, and in that of Litchfield, Me.; also in the granite of Cape Ann, Mass., and of a number of localities in Ireland, and elsewhere. It probably occurs to some extent in metamorphic rocks.

Resemblances to other Minerals.—Micas in thin sections of rocks may generally be distinguished from all other minerals by their sharply defined parallel cleavage cracks, except in sections cut parallel to the cleavage, and by the direction of extinction almost exactly parallel to these cracks. Another feature which is highly characteristic is the mottled appearance exhibited between crossed nicols, often resembling the crinkled fibers of some kinds of wood. This is due to distortion of the flexible laminæ of the mica probably produced in grinding the thin section. It is most noticeable when the mica is near the position of total extinction of the light. It is more noticeable in sections across the plane of cleavage than in those parallel to it. Sections cut parallel to the cleavage are usually characterized by the absence of cracks of any kind. Micas are there-

fore easily distinguished from most minerals except those with mica-like cleavage, such as chlorite, the brittle micas, and talc.

There may be confusion, however, in cases where the cleavage is not noticeable. Thus basal sections of biotite often resemble some sections of similarly colored hornblende, but the interference figure exhibited by the mica is distinctive. Minute crystals or cross-sections of biotite which do not show cleavage cracks may resemble prisms of tourmaline, but the difference in the orientations of the strongly absorbed ray in each mineral is sufficiently characteristic.

Chlorite is distinguished from mica by its low double refraction. The same is true of the brittle micas, chloritoid, ottrelite, and sismondine. Talc is scarcely distinguishable from sericite, having slightly lower refraction and slightly higher double refraction. Its actual determination rests upon chemical distinctions. Kaolin is distinguished from sericite by its low double refraction.

The distinctly alkalic micas, muscovite, lepidolite, paragonite, resemble one another so closely optically that they are only distinguished from one another by chemical tests or flame coloration.

The ferromagnesian micas, phlogopite, biotite, lepidomelane, are distinguished from the purely alkalic micas in most cases by their stronger colors and pleochroism, but are much alike optically. Commonly the lighter-colored varieties are phlogopite, and most biotite exhibits nearly uniaxial interference figures, but their definite identification depends on quantitative chemical analysis.

Laboratory Production.—Micas of several kinds, biotite, muscovite, zinnwaldite, have been produced in the laboratory by a number of different investigators by fusing together various silicates having the constituents of micas with fluorides of sodium, aluminium, magnesium, and fluosilicate of potassium in different combinations. Many attempts to produce mica in other ways have failed, but it has been obtained as microlites in fused rhyolite from Iceland (Morozewicz), and it occurs as a crystallization in some furnace slags. The presence of hydrogen and fluorine in micas indicates the necessity of the presence of these elements in the solutions from which they are to be crystallized.

MARGARITE.

$H_2CaAl_4Si_2O_{12}$.

Chemical Composition.—Margarite is a basic silicate of aluminium and calcium, with other elements in small amounts relating it in composition to the micas. The following analyses show its actual composition compared with the theoretical molecule:

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	H_2O	
$H_2CaAl_4Si_2O_{12}$	30.2	51.3	—	14.0	—	—	—	4.5	=100.00
Nicaria	30.22	49.67	1.33	11.57	tr.	2.31		5.12	=100.22
Cullakenee Mine, N. C.*	29.63	51.19	—	11.28	1.09	1.22	0.20	4.73	
				FeO 0.59		Cr_2O_3 0.13			=100.06
Dudleyville, Ala.†	28.71	52.44	0.39	11.52	0.74	0.67	0.20	5.40	
						Li_2O 0.38			=100.45
Cruger's Point, N. Y.‡	32.73	46.58	5.12	11.04	1.00	—	—	4.49	=100.96

* Sp. gr. 3.064. † Sp. gr. 3.085. ‡ Sp. gr. 3.1.

Alteration.—Slowly and imperfectly decomposed by boiling hydrochloric acid. Alters to a hydrous micaceous mineral called dudleyite.

Monoclinic; axial ratio near that of biotite.

Crystal Forms.—Thin tabular plates parallel to (001), sometimes euhedral, with (001), (010), and one or more inclined prisms, (112), ($\bar{1}$14), and others, yielding six-sided plates with edges at 120°. Commonly anhedral in aggregates of thin laminæ, or dense and massive.

Twinning common, as in mica; twinning plane perpendicular to (001), composition plane (001), often repeated.

Cleavage perfect parallel to (001) as in mica, but the laminæ are rather brittle and not elastic. Yields a percussion-figure like that of mica. H.=3.5–4.5. Sp. gr.=2.99–3.08.

Optical Properties.—Plane of the optic axes perpendicular to (010) and nearly so to (001). Optically negative (−). Acute bisectrix X almost perpendicular to (001). The angle of inclination of X to the normal to (001) is +6° 27′, Tschermak, but varies more widely than in other micas. The angle between the optic axes is large $2E$=76°–80°, Bauer; 120°$_y$, Tschermak; 109° 32′$_r$–128° 48′$_r$, Des Cloizeaux. $\rho < v$. β=1.64–1.65, Becke. $\gamma - \alpha$=0.009 approx., Rosenbusch.

Color.—Grayish, reddish white, pink, yellowish in incident light. In thin section colorless. Luster on basal pinacoid pearly; vitreous on (010); other planes dull.

Modes of Occurrence.—Margarite is found in altered and metamorphosed rocks intimately associated with corundum and emery, as though a product of alteration from them. At Cruger's Point, near Peekskill, N. Y., in mica-schist with staurolite and tourmaline as a result of contact metamorphism. It forms a shell surrounding crystals of corundum at Gainesville, Ga., and in Alabama, and with corundum in numerous localities in this country and elsewhere.

Resemblances to other minerals are chiefly with the micas and other brittle micas. Margarite is distinguished from the colorless micas by its low double refraction and the generally greater inclination of the bisectrix X to the axis c, also by the absence of elasticity in the cleavage laminæ. It is distinguished from chloritoid and ottrelite by the usual absence of color and pleochroism and by its lower hardness.

CHLORITOID—OTTRELITE

Composition: Chloritoid, $H_2(Fe,Mg)Al_2SiO_7$.
Ottrelite, $H_2(Fe,Mn)Al_2Si_2O_9$?

Monoclinic or Triclinic (?), approximating mica in habit.

Twinning similar to that in mica, with crystals oriented as though rotated 120° to one another.

Cleavage rather perfect parallel to (001); also in chloritoid imperfect parallel to (443), inclined about 90° to (001) and about 60° to one another; difficult parallel to (010). Brittle. H. = 6–7. Sp. gr. = 3.3 ottrelite, 3.52–3.57 chloritoid.

Optical Properties: axial plane parallel or nearly parallel to (010). According to Rosenbusch it is perpendicular to (010). Optically positive (+). Acute bisectrix Z inclined to the normal to (001) 12°, Tschermak. Axial angle $2E = 100°$–$118°$ in chloritoid, variable in ottrelite. $\rho > v$ in chloritoid; sometimes $\rho < v$, also $\rho > v$, in ottrelite. $\beta = 1.741$, sismondine; $n = 1.77$ and $\gamma - \alpha = 0.016$, chloritoid. Strong dispersion of the bisectrices.

Color: dark gray, greenish gray, grayish black to black. Often grass-green in very thin plates. In thin section strongly pleochroic, X olive-green, Y blue, Z yellow-green in chloritoid, less in ottrelite. *Luster* on cleavage plates somewhat pearly

Chemical Composition.—Chloritoid and ottrelite are basic silicates of aluminium and ferrous iron with some magnesium in chlori-

toid, and some manganese in ottrelite. The molecular proportions are not alike in the two minerals, as will be seen on comparing the chemical analyses. The composition assumed for chloritoid is $H_2(Fe,Mg)Al_2SiO_7$. The exact composition of ottrelite is uncertain owing to unsatisfactory material for analysis. It is approximately $H_2(Fe,Mn)Al_2Si_2O_9$(?)

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	H_2O	
Chloritoid.									
1. Kosoibrod, Ural	23.01	40.26	—	27.40	—	3.97	—	6.34	=100.98
2. Shetland (clove-brown)	25.36	41.74	3.90	13.93	0.92	6.82	0.90	6.57	=100.14
Sismondine.									
3. St. Marcel	26.03	42.33	4.09	14.32	—	7.30	0.35	6.56	Alk. tr.=100.98
4. Patrick Co., Va. (black-green)	25.03	39.75	—	22.92	1.30	3.32	0.21	6.64	0. Alk. 0.14= 99.31
Ottrelite.									
5. Ottrez	42.48	29.29	3.30	12.11	6.10	2.05	tr.	5.07	=100.40
6. Lierneux	40.55	30.80	3.82	12.46	6.51	0.45	1.29	[4.12]	=100.00

Specific gravity: (1) 3.55; (2) 3.356; (3) 3.42; (4) 3.614; (6) 3.266.

In chloritoid the magnesia varies from 0 to 6.82 per cent. There are varieties containing MnO that have nearly the formula of chloritoid (*salmite* and *masonite*) and are classed chemically with it. In ottrelite the manganese oxide varies from 0 to 8.96 per cent, and there may be a small amount of magnesia present. Some minerals called ottrelite appear to have compositions intermediate between those given above for ottrelite and chloritoid.

Alteration.—Chloritoid and ottrelite are not decomposed by hydrochloric acid, but are completely decomposed by sulphuric acid. The only alteration of these minerals as yet noted is that of ottrelite to chlorite described by C. L. Whittle.

Crystal Forms.—Rarely in tabular crystals with hexagonal outline like mica, formed by the basal pinacoid (001) and (010) with (0·9·10), (051), and (9·9·10), (443), assuming the same axial values as those in biotite. In some crystals the shape is rhombic. Subhedral and anhedral crystals with more or less rounded, lenticular, and irregular shapes are more common. Sections parallel to the basal pinacoid are therefore hexagonal in some instances, rhombic, rounded, or oftener irregularly shaped. Sections highly inclined to the base are elongated, or lath-shaped. The crystals

may be aggregated in radiating bundles, or irregularly curved and bent.

Twinning as in mica with the laminæ in contact on the basal pinacoid (001). In some cases oriented as though rotated 120° in the plane of contact. Frequently polysynthetic, a number of twinned laminæ superimposed on one another. Occasionally the twins are in contact on a marginal plane whose trace on (001) is parallel to (130).

Sections across superimposed twins show twinned lamellæ with slightly different optical orientation because of the inclination of the bisectrices Z, Y to the basal pinacoid. Twins in the second position, adjacent in the plane of (001), are recognized in sections in this plane by the orientation of the planes of the optic axes in each part of the twinned crystal, which make angles of 120° with one another.

Cleavage.—Parallel to (001) rather perfect, but not so much so as in mica. In chloritoid there are other less perfect cleavages nearly at 90° to the basal; one is parallel to a prism whose faces intersect at about 60°; the other is difficult and is parallel to (010). The latter appear as poorly defined interrupted cracks in thin section. There are also in some instances irregular cracks traversing the crystals in various directions, or in more or less parallel lines as though produced by the shearing of the rock mass. H.=6–7. Sp. gr.=3.52–3.57, chloritoid; 3.42–3.614, sismondine; 3.3, ottrelite.

Optical Properties.—Axial plane parallel to (010) in most cases, but apparently slightly inclined to it, 1° to 1° 30′ in sismondine from St. Marcel (Des Cloizeaux). This may be due to twinning or bending of crystal plates. According to Rosenbusch the plane of the optic axes is normal to the plane of symmetry (010), $X \parallel b$, which agrees with the observed horizontal dispersion of the optic axes. The acute bisectrix is Z, the optical character is positive (+). The acute bisectrix is nearly normal to (001), but the inclination to the crystal axis c varies more than in mica. $Z \wedge c = 0°$ to 12° or 21°. There is strong dispersion of the acute bisectrix $Z_\rho \wedge c > Z_\nu \wedge c$, reaching as much as 2° to 4° in chloritoid. The dispersion of the bisectrices is greater the greater its inclination to c. The index of refraction is moderately high.

Sismondine, Val de Chisone		$\beta = 1.741$	$\beta - \alpha = 0.0098$	Rosenbusch
Chloritoid, Lainiciu		$n = 1.77$	$\gamma - \alpha = 0.016$	Duparc and Mrazec
—	—	$n = 1.75$	$\gamma - \alpha = 0.007$	Lane
—	—	—	$\gamma - \alpha = 0.015$	Lacroix

The angle of the optic axes is generally large, but varies considerably. Axial dispersion is distinct and horizontal, $\rho > v$ in chloritoid; $\rho < v$, also $\rho > v$, in ottrelites.

Sismondine, Zermatt	$2E_r = 111° 50'–117° 48'$		$2E_{gr} = 108° 44'$	Des Cloizeaux
" Val de Chisone	$2E_r = 101° 26'$		$2E_{gr} = 91° 22'$	Des Cloizeaux
" "	$2E_r = 95° 5'$	$2E_{wh} = 88° 40'$	$2E_{bl} = 78° 50'$	Rosenbusch
Chloritoid, Ile de Groix		$2E = 65°–70°$		von Lasaulx
" Morbihan		$2V = 45°–55°$		Barrois

Color.—Dark green, greenish gray, grayish black, rarely grass-green. In thin section strongly pleochroic in chloritoid, less so in ottrelite. X olive-green, Y plum-blue to indigo-blue, greenish blue, Z yellowish green to colorless. The colors of Y and Z appear in sections parallel to (001). In sections perpendicular to (001) the colors of X and Y or Z appear according to the position of the section with respect to the plane of symmetry.

Zonal structure, produced by differences of color and presumably differences in composition, is sometimes developed, especially in the Canadian chloritoids, the central portion being darker-colored than the margin. A structure resembling the so-called hour-glass structure in augite is also present in some occurrences. It appears to be independent of the multiple twinning when present.

Inclusions.—Chloritoid and ottrelite commonly inclose crystals of the minerals associated with them in the rocks, such as quartz, rutile, tourmaline, zircon, etc. These inclusions are often abundant and have a somewhat parallel arrangement corresponding to the schistosity of the rock.

Modes of Occurrence.—*Chloritoid* and *ottrelite* occur wholly in the crystalline schists, especially the phyllites and quartzites, also in mica-schist. The original chloritoid occurs with mica and cyanite at Kosoibrod in the Ural. It occurs with ottrelite in schist in the Ardennes, in micaceous and argillaceous schists in Canada. *Sismondine* accompanies glaucophane at Zermatt, Switzerland, in the Val de Chisone, Piedmont and on Ile de Groix, Brittany. It occurs at St. Marcel in chlorite-schist. *Masonite* is found in an argillaceous schist at Natick, R. I. *Ottrelite* occurs in argillaceous schist near Ottrez, Luxembourg, also in Michigan, Vermont, and elsewhere.

These minerals lie scattered in all directions through the rocks independent of the schistosity, though they may lie parallel to one another in places. They sometimes occur in fan-shaped, sheaf-like clusters of crystals.

Resemblances.—Chloritoid and ottrelite are most like margarite, the micas and the chlorites, but they are distinguished from these minerals by the combination of their optical characters, namely, comparatively high refraction, low double refraction, strong dispersion of optic axes and bisectrix, and the characteristic pleochroism.

CHLORITE GROUP.

COMPOSITION:

In part $\begin{cases} m[H_4(Mg,Fe)_3Si_2O_9]. \\ n[H_4(Mg,Fe)_2Al_2SiO_9]. \end{cases}$

MONOCLINIC. In part PSEUDO-TRIGONAL.

Clinochlore, $a:b:c=0.57735:1:2.2772$. $\beta=89°\ 40'$.

Twinning: (1) Twinning plane perpendicular to (001) in the zone of (001) (112); contact plane in some cases (001), in others an irregular face yielding contact twins. (2) Twinning plane (001), which is also the contact plane. (3) A possible twinning having twinning plane perpendicular to (001) in the zone of (001) (130).

Cleavage: highly perfect parallel to (001). Laminæ flexible, tough, and but slightly elastic. Percussion and pressure figures as in mica. H. = 2–2.5. Sp. gr. = 2.65–2.96, varies with the composition.

OPTICAL PROPERTIES: in part biaxial, in part uniaxial. Plane of the optic axes parallel to (010). The acute bisectrix is Z, optically positive (+), and is slightly inclined to the crystal axis c, almost normal to (001). The uniaxial varieties in some cases optically positive (+), in others negative (−). $2E$ varies from 0° to 89°. Index of refraction moderate, ranging from $\alpha=1.576$, $\gamma=1.579$ to $\alpha=1.586$, $\gamma=1.596$; double refraction low, $\gamma-\alpha=0.003$ and 0.010.

Color: green of various shades to yellowish and white, also pink. In thin section pleochroic, in shade and tones of green and yellow, less often brown, red, violet, and blue. *Luster* on cleavage surface somewhat pearly.

Chemical Composition.—The minerals of this group exhibit considerable variation in proportions, but agree in being silicates of aluminium with ferrous iron and magnesium and combined water. In some varieties ferric iron is present, in others chromium, also manganese. No simple statements or formulæ can be given for many of the chlorites, but for those occurring in larger and better developed crystals, called *orthochlorites* by Tschermak, he has suggested the mixture of two silicate molecules, one corresponding to serpentine, the other to a variety of chlorite, amesite:

$$H_4(Mg,Fe)_3Si_2O_9 = Sp.$$
$$H_4(Mg,Fe)_2Al_2SiO_9 = At.$$

The chief orthochlorites are:

Penninite, Clinochlore,	$H_8(Mg,Fe)_5AlSi_3O_{18}$	$=SpAt.$
Prochlorite,	$H_{40}(Fe,Mg)_{23}Al_{14}Si_{13}O_{90}$	$=Sp_3At_{17}.$
Corundophilite,	$H_{20}(Fe,Mg)_{11}Al_8Si_6O_{45}$	$=SpAt_4.$
Amesite,	$H_4(Mg,Fe)_2Al_2SiO_9$	$=At.$

The chemical composition of some varieties of orthochlorite is shown in the accompanying table of analyses.

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	H_2O	
Clinochlore.								
1. Achmatovsk	31.31	18.34	2.10	0.77	34.25	tr.	13.33	Na_2O 0.17 K_2O 0.06 = 100.33
2. West Chester, Pa.	29.87	14.48	5.52	1.93	33.06	—	13.60	NiO 0.17 Cr_2O_3 1.56 = 100.19
3. Cape Wrath	31.03	14.85	5.73	17.42	17.42	0.36	12.48	MnO 1.00 = 100.29
Leuchtenbergite.								
4. Amity	30.28	22.13	—	1.08	34.45	—	12.61	= 100.55
Kotschubeite.								
5. Ufaleisk	32.73	13.43	2.15	—	35.40	—	12.63	Cr_2O_3 4.19 = 100.53
6. Green Valley, Cal.	31.74	6.74	—	1.23	35.18	0.18	13.04	Cr_2O_3 11.39 NiO 0.49 = 99.99
Penninite.								
7. Zermatt	33.71	12.55	2.74	3.40	34.70	0.66	12.27	= 100.03
Kammererite.								
8. Texas, Pa.	33.28	10.60	—	1.60	36.00	—	12.95	Cr_2O_3 4.72 Alk. 0.35 = 99.50
9. Lake Itkul	30.58	15.94	—	3.32	33.45	—	12.05	Cr_2O_3 4.99 = 100.33
Prochlorite.								
10. Zillerthal	26.02	20.16	1.07	28.08	15.50	0.44	9.65	= 100.92
11. Washington, D. C.	25.40	22.80	2.86	17.77	19.09	—	12.21	F tr. MnO 0.25 = 100.38
Corundophilite.								
12. Chester, Mass.	24.77	25.52	—	15.19	21.88	—	11.98	= 99.34

Specific gravity: (1) 2.648; (3) 2.823; (4) 2.680; (7) 2.693; (10) 2.955; (11) 2.835; (12) 2.83.

The chlorites commonly occurring in fine scales and fibers are called *leptochlorites*. Their composition is less simply expressed,

and since the many varieties recognized in mineralogy cannot yet be distinguished from one another under the mircoscope they are classed in petrography under the simple head of chlorite. For this reason they are not described in detail.

Alteration.—The orthochlorites are wholly decomposed by sulphuric acid. Penninite is partly decomposed by hydrochloric acid, and the leptochlorites are completely decomposed by this acid, with the separation of silica in various forms in different instances. The chlorites are secondary minerals resulting from the alteration of various silicates. The further alteration of these secondary minerals has not been described, except to state that they may be finally replaced by iron oxides, carbonates, and quartz.

Crystal Form. — *Clinochlore* is monoclinic, with $a:b:c=0.57735:1:2.2772$, $\beta=89°\ 40'$. Often in tabular crystals flattened parallel to (001) with hexagonal outline, sometimes prismatic with (112) prominent, also twelve-sided. There are trigonal and rhombohedral crystals resembling penninite formed by planes in the zones $(001)(\bar{1}01)$, $(001)(130)$, and $(001)(1\bar{3}0)$. There are several sets of zones developed in different cases, whose traces on (001) intersect at 60° or 120°, and as the crystals may also be twinned in one of these zones the identification of crystal forms is often difficult.

The forms commonly developed on euhedral crystals are $c(001)$, $b(010)$, $u(227)$, $m_0(112)$, $o(\bar{1}11)$, $\mu(112)$, $v(132)$, $g(261)$, $f(\bar{4}01)$, $j(\bar{3}\bar{1}\cdot0\cdot30)$, $\phi(9\cdot\bar{2}\bar{7}\cdot17)$, and others. Some of the combinations are shown in Figs. 1, 2, and 3.

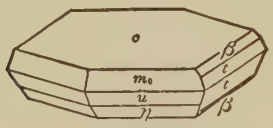


FIG. 1.

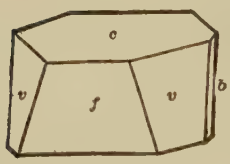


FIG. 2.

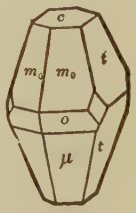


FIG. 3.

FIG. 4.

Penninite is rhombohedral in habit, but is strictly pseudorhombohedral and may be referred to the same monoclinic axes as clinochlore. The crystals are thick tabular with trigonal outline, sometimes in

apparent rhombohedrons, which are often steep, also in tapering six-sided pyramids (Fig. 4).

Prochlorite and *corundophilite* occur in six-sided tables or prisms and not in the well-developed forms sometimes assumed by the two first-named chlorites.

Euhedral crystals occur in cavities in rocks and not as part of the body of a rock. In this case they are generally anhedral, more or less hexagonal or trigonal in some instances, but oftener irregularly outlined plates or scales, frequently bent and distorted. They are frequently grouped in spherulitic aggregates. When in microscopic crystals they may appear like minute scales or fibers, or ill-defined particles.

Twinning.—(1) In general, according to the same law as in mica, twinning plane perpendicular to (001) in the zone (001)(110), composition plane in some cases (001), as in Fig. 5, the plane of the optic axes in the two parts intersecting at 60°. In other cases the twinned parts lie in one plane adjacent to one another along irregular planes, as in Fig. 6, or they may form a trilling (Fig. 7), or a crystal

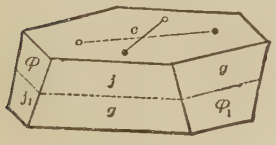


FIG. 5.

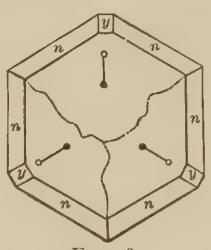


FIG. 6.

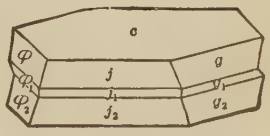


FIG. 7.

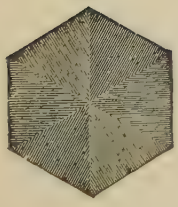


FIG. 8.

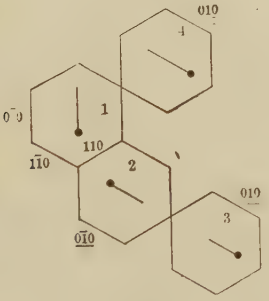


FIG. 10.

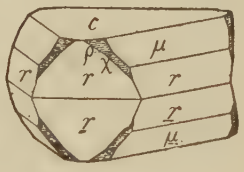


FIG. 9.

with six parts (Fig. 8). (2) A second mode of twinning has (001) for twinning and composition plane. This is specially common in penninite. The two parts are in this case reversed 180° (Fig. 9). The relation of these two modes of twinning to one another is shown

in Fig. 10. Plates 1 and 2 are twinned according to the mica law, Plates 2 and 3 according to the penninite law. When both of these modes of twinning occur on one crystal, plates appear as 1 and 4, as though twinned on a plane perpendicular to (001) in the zone (001)(130).

It is possible to explain the apparently uniaxial character of penninite by assuming a highly developed multiple twinning of biaxial plates like clinochlore.

Cleavage.—Highly perfect parallel to (001), the laminæ being flexible, tough, and but slightly elastic. These chlorites exhibit percussion figures and pressure figures like those in mica and are similarly oriented. H.=1–2, prochlorite; 2–2.5 in other varieties. Sp. gr.=2.65–2.78, clinochlore; 2.6–2.85, penninite; 2.78–2.96, prochlorite; 2.90, corundophilite.

Optical Properties.—The chlorites are biaxial in part, with a variable angle between the optic axes that reaches 0° in penninite, which behaves as a uniaxial crystal. The plane of the optic axes is parallel to (010), the plane of symmetry. The acute bisectrix Z is inclined slightly to the normal to (001) in the obtuse angle β. The angle of inclination is greater in crystals having larger optical angles, being nearly zero in those that are uniaxial.

		$Z \wedge c$	$2E$	β	$2V$	Disp.	
Corundophilite,	Chester, Mass.	8° 20′	80°	1.583	46° 40′	$\rho < v$	Tschermak
Clinochlore,	West Chester	7° 10′	89° 41′	1.583	51° 31′		"
"	Zillerthal	6° 45′	83°	1.583	48° 30′		"
"	Achmatovsk	2° 30′	32°	1.588	20°	$\rho < v$	"
"	"		12°, 5°, 1°, and intermediate values				Tschermak
"	Ala, Piedmont		65°–44°				"
"	Texas, Pa.		60°–20°				"
Prochlorite,	Prägraten	2°	30° and more				"
"			varies from 30° to 0°			$\rho < v$	"
Leuchtenbergite,	Ural		15°–0°				"
"	Amity, N. Y.		29°–10°				"
Kotschubeyite,	Ural		36°–0°				"
Penninite,	—	0°	0°, occasionally as high as 60°				—
Kämmererite,	Texas, Pa.		0°–20°				Tschermak

Numerous other observations have been recorded by Des Cloizeaux and others. The axial angle is not only different for different crystals sometimes in one rock, but even in different parts of one crystal. The dispersion for all optically positive crystals is $\rho < v$, but in some varieties of biaxial penninite which are negative it is $\rho > v$. The dispersion of one optic axis is much more pronounced than that of the other, in consequence of the inclined dispersion. The bisectrix Z

is noticeably dispersed in some instances. Tschermak found on clinochlore, West Chester,

$$2E_r = 87° 45', \quad \beta = 1.580, \quad 2V = 50° 45', \quad Z \wedge c = 7° 8'.$$
$$2E_{bl} = 94° 54', \quad \beta = 1.593, \quad 2V = 53° 13', \quad Z \wedge c = 7° 40'.$$

The refraction is moderate, about the same as that of mica, and the double refraction is low in clinochlore, about that of quartz, and very low in penninite, about .001, in some cases as high as .003.

		α	β	γ	$\gamma - \alpha$	
Clinochlore, Ural		1.585	1.588	1.596	0.011	Lévy and Lacroix
"	—	1.5854_y	1.5863_y	1.5955_y	0.0101_y	Zimanyi
"	West Chester	1.586	1.586	1.596	0.010	Königsberger
Penninite,	Zermatt	1.576	—	1.579	0.003	Lévy and Lacroix
"	—	1.576	—	1.577	0.001	Des Cloizeaux
"	Zermatt	1.575	—	1.576	0.001	Haidinger
"	Rümpfischwäng	1.5821_y	—	1.5832_y	0.0011_y	Zimanyi

The distinctly blue interference color often exhibited by penninite is due to the difference in the optical constants for different light wave lengths, the optic angle being 0° for some colors and having an appreciable value for others. In this case it is 0° for yellow, and the resulting interference color is indigo-blue.

Color.—Various shades and tones of green, rarely brown, nearly colorless in some varieties poor in iron, occasionally violet, rose-red and pink in those containing chromium. In thin section the colored chlorites are noticeably pleochroic. The following observations were made by Tschermak, except that on kotschubeyite from Green Valley, Cal., by Lindgren:

	Body-color.	*X*	*Z*
Clinochlore, Achmatovsk	black-green	dark green	greenish yellow
" "	black-brown	dark brown	brownish yellow
" Texas, Pa.	dark green	emerald-green	hyacinth-red
" " "	dark green	leek-green	yellowish green
" Pfitsch, Tyrol	dark green	leek-green	greenish yellow
" Ala, Piedmont	gray-green	olive-green	greenish yellow
Prochlorite, Fasch	olive-green	yellowish green	brownish
Penninite —	olive-green	emerald-green	brownish red, brown, yellow
" —	leek-green	blue-green	yellow
Kotschubeyite, Ural	dark rose-red	blue-violet	bright carmine-red
" Green Valley, Cal.	rose-red	purplish	yellowish red
Kämmererite, Texas, Pa.	peach-blossom red	violet	hyacinth-red
" Kraubat	peach-blossom red	bluish	red

Modes of Occurrence.—Chlorite is a common constituent of the crystalline schists, forming the preponderant mineral in some schists, e.g., chlorite-schist. It is present in phyllites, mica-schists, and other rocks of this category. Chlorite occurs as a secondary mineral in all kinds of igneous rocks, resulting from the alteration of the aluminous ferromagnesian minerals, amphiboles, pyroxenes, micas, etc. It also forms from the combination of the constituents of aluminous minerals, such as the feldspars, with those of ferromagnesian minerals, so that chlorite may be developed in any part of a rock. It is one of the commonest alteration-products and gives the greenish color to many somewhat altered igneous rocks and to many metamorphic ones. Chlorite often forms pseudomorphs after the ferromagnesian minerals from which it has developed. When it is derived from biotite it frequently preserves the cleavage and form of the original mineral, chlorite crystals developing in parallel orientation to the biotite. When it results from amphibole and pyroxene it usually takes the form of an irregularly aggregated mass of minute scales, appearing like fibers in cross-section. In some cases it is arranged in spherulitic aggregates. The microscopic crystals of chlorite cannot be identified optically as belonging to a particular variety and are described simply as chlorite. The larger crystals may be identified and are known to occur in certain localities. Among the many occurrences already known, a few may be mentioned as examples.

Clinochlore occurs in chlorite-schist with garnet, diopside, and apatite at the Achmatovsk mines in the Ural; in chlorite-schist in the Zillerthal, Tyrol; in serpentine with magnesite at West Chester, Pa.; and in many other parts of the world. It is probably the commonest variety. *Leuchtenbergite* is found at Amity, N. Y., in coarse-grained calcite together with pale-green hornblende, phlogopite, fluorite, and particles of graphite, apparently the result of contact metamorphism; also in the Ural and at Traversella. *Kotschubeyite* is found in veins in serpentine and chlorite in the chlorite-schists in the district of Ufaléjsk, southern Ural, and in a similar manner in Green Valley, Cal. *Penninite* is common in crystalline schists. It is found in numerous localities in the neighborhood of Zermatt, Switzerland, in the Zillerthal, Tyrol, and elsewhere. *Kämmererite* occurs with penninite in the localities just mentioned; also with clinochlore and kotschubeyite at Texas, Pa., and at other localities in the United States. *Prochlorite* occurs in the same manner as the other chlorites. It sometimes forms curved prismatic vermiform crystals. *Corundophilite* is

associated with corundum and emery in more or less altered metamorphic rocks, and is found at Asheville, N. C., Chester, Mass., and elsewhere.

Of the leptochlorites there are a number of varieties, daphnite, cronstedtite, thuringite, diabantite, delessite, etc., but, as already remarked, they are not distinguishable from one another optically. *Delessite* frequently forms the amygdules filling vesicular cavities in basalts. It often coats the walls of the cavity with successive layers, appearing in cross-section as concentric bands. In some cases it forms minute spherulites.

Resemblances.—The principal varieties of orthochlorites are distinguished from one another optically by the following characteristics:

In clinochlore and prochlorite, generally distinctly biaxial character, optically positive (+); penninite, uniaxial character, in some cases positive, in others negative. In clinochlore somewhat higher double refraction, as in quartz; in penninite extremely low double refraction, with indigo-blue interference color. In clinochlore twin laminæ often noticeable in cross-section, and colors and pleochroism somewhat stronger than in penninite. The other varieties are recognized by their colors and biaxial or uniaxial character. The chlorites resemble some micas, but are distinguished from them by lower double refraction, and optically positive character in most cases.

Chlorite resembles serpentine in color, refraction, and double refraction. Serpentine differs from all chlorites, except optically negative penninite, in being optically negative with the bisectrix X perpendicular to the direction of the cleavage surface; but possibly optically positive in the fibrous forms, with the bisectrix Z parallel to the length of the fibers. Serpentine and optically negative penninite can be distinguished from one another only by chemical means.

SERPENTINE.

Composition: $H_4Mg_3Si_2O_9$.

Monoclinic or orthorhombic (?).

Cleavage: pinacoidal, parallel to (010) (Dana), sometimes distinct, also prismatic (50°) in fibrous varieties, chrysotile. Fracture usually conchoidal or splintery. H. = 2.5–4, rarely 5.5. Sp. gr. = 2.50–2.65.

Optical Properties. Biaxial, axial plane parallel to (100), bisectrix X perpendicular to (010), Z parallel to length of fibers. Optically negative (−) in lamellar varieties, positive (+) in chrysotile. $2E$ variable, from 16° to 98° Tschermak. $2V = 20°$ to 90° Lévy and Lacroix. Refraction low. $\alpha = 1.560$, $\beta = 1.570$, $\gamma = 1.571$, $\gamma - \alpha = 0.011$ in antigorite, Lévy and Lacroix; 0.013 in chrysotile, Rosenbusch; $\rho > v$.

Color: various shades and tones of green, sometimes brownish red, yellow, nearly white. In thin section sometimes faintly pleochroic. *Luster:* subresinous to greasy, pearly to earthy.

Chemical Composition.—Serpentine is a magnesium silicate with considerable combined water, $H_4Mg_3Si_2O_9$, or $3MgO \cdot 2SiO_2 \cdot 2H_2O$= SiO_2 44.1, MgO 43.0, H_2O 12.9=100. It often contains FeO, replacing MgO, and sometimes NiO. Some varieties contain small amounts of aluminium and appear to be intermediate in composition between serpentine and chlorite; serpentine and negative penninite resemble one another closely optically, so that Tschermak and others suggest a probable transition from one to the other.

Alteration.—Serpentine is decomposed by hydrochloric and sulphuric acids. Serpentine alters by the addition of water and eventual decomposition into silica in the form of opal, chalcedony, or quartz, and into carbonates.

Crystal Forms.—Euhedral crystals of serpentine are not known. It always forms a decomposition product from other minerals and occurs as pseudomorphs after them or in irregularly shaped crystals or aggregations of microscopic crystals. It is in some cases laminated, in crystals cleaving into megascopic laminæ, as in *antigorite*, or into microscopic scales often oriented in various positions in the serpentine mass. In many cases it is fibrous, as in *chrysotile*, in which the fibers are parallel to one another. They may also be more or less divergent or radiating, as in *metaxite* and *picrolite*. But these different modes of arrangement may occur in one mass of serpentine.

Cleavage.—Pinacoidal, sometimes distinct, in antigorite varieties, assumed to be parallel to (010); laminæ flexible to brittle, inelastic. Also prismatic, well developed, in chrysotile varieties, with an angle of 50°; fibers often flexible and silk-like. Fracture in massive varieties subconchoidal to splintery.

Optical Properties.—Biaxial, with the plane of the optic axes perpendicular to the pinacoidal cleavage, with the bisectrix X normal to the laminæ. According to Dana the pinacoidal cleavage is parallel to (010), according to Lacroix it is (100). To conform with the pinacoidal cleavage in chlorite and talc it would seem advisable to consider the cleavage pinacoid in serpentine (001). In laminated serpentine, antigorite, the bisectrix X is the acute bisectrix; the optical character is negative (−). In fibrous serpentine the bisectrix Z is parallel to the length of the fibers and is the acute bisectrix. This variety is therefore optically positive (+). The plane of the optic axes is in the plane of the longer diagonal of the rhombic

cross-section of the prismatic cleavage. If the axis of the fibers is c, then the optical orientation is $X \parallel b$, $Y \parallel a$, $Z \parallel c$. Assuming the pinacoidal cleavage to be basal (001), then $X \parallel c$; and if the optical orientation remains the same in the laminated and fibrous varieties, it is necessary to assume that the fibers are prisms parallel to either a or b.

The angle between the optic axes varies within wide limits. For antigorite, Tschermak found $2E = 16°–98°$, $\rho > v$. For chrysotile from Reichenstein, $2E = 16°\ 30'$, Reusch; from Amelose, $2E = 50°$, Brauns.

The refraction is low. On antigorite from Canton Wallis, $\alpha = 1.560$, $\beta = 1.570$, $\gamma = 1.571$, $\gamma - \alpha = 0.011$, Lévy and Lacroix; $\beta_r = 1.574$, Des Cloizeaux. On antigorite from Kosgrube, $\alpha_y = 1.490$, $\beta_y = 1.502$, $\gamma_y = 1.511$, $\gamma - \alpha = 0.021$, Hamberg. On chrysotile from Canada, $n = 1.54$, $\gamma - \alpha = 0.013$ as a maximum, Rosenbusch. The double refraction is slightly higher than that of quartz, about that of clinochlore.

Color.—Leek-green, oil- and siskin-green to blackish green; brownish red or yellow, rarely white. In thin section colorless to green, yellowish, brownish, seldom red. Pleochroism faint, somewhat as in chlorite.

Inclusions in serpentine are in part those present in the minerals from which serpentine has formed, together with remnants of the partly altered original mineral. They may also be minerals formed at the same time as the serpentine, as magnetite and hematite, carbonates and silica in the form of opal or quartz.

Modes of Occurrence.—Serpentine occurs chiefly as an alteration-product of non-aluminous ferromagnesian minerals, olivine, pyroxene, amphibole, and others in igneous and metamorphic rocks. It may fill the space formerly occupied by the original mineral as a pseudomorph, or it may be deposited in other parts of the rock in cavities and veins, or replacing other minerals. The commonest source of serpentine is olivine, in which case the serpentine forms along the surface of the crystal and of cracks through it, producing fibers or scales nearly perpendicular to the surfaces of the crystal fragments, the central portion of a fragment eventually being replaced by serpentine fibers in various orientations. The resulting pseudomorph in section appears as a network, the original cracks representing the cords. These are sometimes marked by the deposition of iron oxide, magnetite, or hematite, resulting from the oxidation of the ferrous iron in the olivine. Or the serpentine may be colored more strongly near the cracks by greater content of iron oxide in

their proximity. In some instances there are subordinate networks within the principal network, in which the smaller or secondary cracks are occupied by veins of fibrous serpentine instead of iron oxide.

Lamellar serpentine has been developed from olivine in the olivinefels of Norrland, Sweden, and in serpentines of the Tyrol. It is probable that the red lamellar alteration-product commonly formed from olivine and called iddingsite is a lamellar serpentine, antigorite, colored by red oxide of iron.

The formation of serpentine is often accompanied by that of tremolite and actinolite, less often of talc. Serpentine results from the alteration of enstatite and hypersthene, orthorhombic amphibole, and occasionally from that of aluminous and calcic varieties of pyroxenes and amphiboles. The resulting structure of the serpentine is not specially characteristic, except in the case of certain amphiboles described by Weigand, in which the serpentine fibers bear the same relation to the cleavage cracks as they do to the fracture cracks in olivine. The cross-cleaved antigorite of the Alps, described by von Drasche and Hussak, has been considered the result of alteration from pyroxene.

Resemblances to Other Minerals.—Serpentine is most like chlorite, especially optically negative penninite, from which it can be distinguished only by chemical means. In general, chlorite is more pleochroic and is optically positive (+). The peculiar netlike structure of serpentine when altered from olivines and some amphiboles is distinctive.

Laboratory Production.—Serpentine has been produced by A. Gages in a transparent mass by placing a solution of gelatinous silicate of magnesium in a dilute solution of potash. The serpentine deposited after some months' standing.

TALC.

$H_2Mg_3(SiO_3)_4$.

Chemical Composition.—An acid metasilicate of magnesium. $H_2O \cdot 3MgO \cdot 4SiO_2 = SiO_2$ 63.5, MgO 31.7, H_2O 4.8 = 100. Nickel is sometimes present in small amount. Not decomposed by acids.

Orthorhombic or **Monoclinic** (?). Euhedral crystals not known. Rarely in tabular crystals, hexagonal or rhombic in outline, with a prismatic angle of 60°. Commonly foliated, also in globular and stellate groups, sometimes compact, fibrous, and cryptocrystalline.

Cleavage perfect parallel to (001); laminæ flexible but inelastic. Percussion figure as in mica, but with the leading line parallel to the axis *b*. Sectile. H.=1. Sp. gr.=2.7–2.8.

Optical Properties.—Biaxial, plane of optic axes parallel to (100). The acute bisectrix *X* normal to (001). Optically negative (−). Axial angle small and variable, $2E=6°$–$40°$. Indices of refraction low, double refraction high. On talc from Pennsylvania, $\alpha_y=1.539$, $\beta_y=1.589$, $\gamma_y=1.589$, $\gamma-\alpha=0.050$, Zimanyi; $\gamma-\alpha=0.038$–0.043, Siberia, Michel-Lévy. Dispersion noticeable, $\rho>v$. Sections of spherulitic aggregates between crossed nicols in parallel light yield interference crosses with positive character and brightly colored quadrants, according to Rosenbusch.

Color.—Apple-green to white or silvery white, also greenish gray to dark green. Brownish and reddish when impure. In thin section colorless. Luster pearly on cleavage surface.

Modes of Occurrence.—Talc is commonest in the crystalline schists, forming talc-schist, steatite, or soapstone, and also occurring in other rocks, as serpentine, chloritic schist, and dolomite. It often contains crystals of carbonates, actinolite, tourmaline, magnetite, and rutile. In igneous rocks it is an alteration-product of non-aluminous magnesian silicates, such as olivine, enstatite, and tremolite, but is not so frequently developed as serpentine.

Resemblances.—Talc is most like muscovite in the microscopic form of sericite, from which it is not distinguishable optically, the only means of distinction being chemical. It also resembles brucite, which, however, is optically positive and uniaxial.

GLAUCONITE.

Silicate of iron and potassium with aluminium and water, in variable proportions, and usually mixed with other materials. Some varieties are entirely decomposed by hydrochloric acid, while others are not attacked.

Amorphous, resembling earthy chlorite. Usually in small globular masses or grains of somewhat varied shapes. Granular in texture; the larger globules are sometimes radially fibrous. H.=2. Sp. gr.=2.2–2.4.

Optical Properties.—Biaxial in lamellar aggregation, with $2E=30°$–$40°$, but varying in some places to 0°, according to L. Cayeux. Index of refraction low, double refraction in lamellar varieties as strong as in mica (Cayeux), weak in minutely grained aggregates probably from compensation by overlying particles.

Color.—Olive-green, blackish green, yellowish to grayish green. In thin section yellow-green, sea-green to dark green, sometimes blue-green. Pleochroic in lamellar varieties: dark green parallel to the lamellæ, bright yellow at right angles to the lamellæ.

Modes of Occurrence.—Chiefly in sedimentary rocks, as in the greensands of the Cretaceous, rarely in limestones of other periods. Often forms casts of the shells of rhizopods, even of recent date, being found in deep-sea soundings. Glauconite also occurs in amygdaloidal cavities in igneous rocks.

KAOLINITE.

$H_4Al_2Si_2O_9$.

Composition.—$2H_2O \cdot Al_2O_3 \cdot 2SiO_2 = SiO_2$ 46.5, Al_2O_3 39.5, H_2O 14.0 = 100. Silicate of aluminium with combined water. Insoluble in hydrochloric acid, slowly soluble in hot sulphuric acid.

Monoclinic; $a:b:c = 0.5748:1:1.5997$, $\beta = 83° 11'$. Euhedral crystals are bounded by (010), (001), (110), ($\bar{1}11$). Crystals are usually thin plates parallel to (001), with hexagonal or rhombic outline, having edges at 60° and 120°. Also in irregularly shaped scales. Twinning as in mica, with adjacent parts making six sectors as in clinochlore. Also in superimposed twinned laminæ. Often in fan-like aggregates. Usually in a clay-like mass, friable or mealy.

Cleavage perfect parallel to (001); laminæ flexible, but inelastic. A cleavage parallel to the hexagonal edges of the basal pinacoid, corresponding to the cracks of a percussion figure, has been observed by H. Reusch. H. = 2–2.5. Sp. gr. = 2.6–2.63.

Optical Properties.—Biaxial, with the plane of the optic axes perpendicular to (010) and inclined to (001), so that the acute bisectrix X makes an angle of about 20° with the normal to (001), lying in the acute angle β. The bisectrix Z is normal to (010). Optically negative (−). Axial angle 90° in some occurrences, small to almost 0° in others. Index of refraction low, about 1.54, near that of Canada balsam. Double refraction low, $\gamma - \alpha = 0.008$ approx.

Color.—White, grayish, yellowish, sometimes brownish, bluish, or reddish. In thin section colorless. Luster pearly on cleavage surface. In mass pearly to dull.

Modes of Occurrence.—Chiefly the result of the alteration of aluminous silicates, as feldspar, nephelite, scapolite, etc. Usually in minute scales in confused aggregation. Often accumulated in large deposits from the alteration of aluminous rocks. Usually containing

numerous impurities in the form of quartz and other minerals. Also in veins associated with ore deposits, and occasionally in well-crystallized forms in cavities in quartz veins, as at the National Bell Mine, Silverton, Colo. Various modifications of kaolinite have received different names, as *nacrite, pholerite, ancudite, rectorite,* etc.

Resemblances.—Kaolinite resembles muscovite, talc, and hydrargillite, but is distinguished from these minerals by its lower refraction and double refraction.

BRAVAISITE.

A hydrous silicate of aluminium, composed of SiO_2 51.4, Al_2O_3 18.9, Fe_2O_3 4.0, MgO 3.3, CaO 2.0, K_2O 6.5, H_2O 13.3 = 99.4. Partially attacked by acids.

In thin layers and schistose masses consisting of fine fibers or scales mostly in parallel position, in places intersecting at right angles. Unctuous to the touch. Paste-like when wet. When dry, H. = 1–2. Sp. gr. = 2.6.

Optically negative (−); acute bisectrix X nearly normal to plane of schistosity; $2E = 40°$ approx. Extinction parallel to the axis of the fibers. Double refraction strong. Color gray to greenish gray. Appearance clay-like. Occurs in layers in the coal and bituminous schists of Noyant, Dept. Allier, France.

ASTROLITE.

$$H(Na,K)_2(\overset{III}{Fe}OH)\overset{III}{Fe}Al(SiO_3)_5.$$

SiO_2 52.14, Al_2O_3 8.15, Fe_2O_3 13.05, FeO 12.01, Na_2O 6.62, K_2O 5.20, H_2O 2.83 = 100. Not attacked by hydrochloric or sulphuric acids. Water given off above 200°.

In spheroids 2 to 6 mm. in diameter, radially fibrous, composed of microscopic scales or plates. H. = 3.5. Sp. gr. = 2.78, average. Optically negative (−); acute bisectrix X normal to plates; extinction parallel to length of fibers; $2E = 48°$ approx.; dispersion weak, $\rho > v$; refraction noticeably higher than that of Canada balsam, $\gamma - \alpha = 0.020$–0.022. Color green-yellow; in thin section siskin-yellow with green tint. Pleochroism, siskin-yellow parallel to the length of fibers, pale yellow to colorless at right angles to this direction. Luster on cleavage face vitreous to pearly. Astrolite occurs as inclusions in black quartz-schist and limestone in diabase tuff near Neumark in Saxony.

MOSANDRITE GROUP.

Johnstrupite.
Mosandrite.
Rinkite.

Chemical Composition.—Complex silicates of the cerium metals, calcium and sodium chiefly, with titanium and fluorine. For johnstrupite Brögger suggests a formula analogous to that of epidote, to which these minerals show crystallographic resemblances:

$$\left[\begin{matrix}\overset{IV}{F_6R_3}\\ \overset{III}{FR}\end{matrix}\right](\overset{I}{R_2})_4\overset{II}{R_{13}}\overset{III}{R_2}(SiO_4)_{12}.\quad \overset{I}{R}=Na,H;\ \overset{II}{R}=Ca,Mg;\ \overset{III}{R}=Ce,Y,Al,Fe;\ \overset{IV}{R}=Ti,Zr.$$

The group in the brackets is regarded as corresponding to the bivalent group $(\overset{III}{R}OH)$ in epidote. Similar formulas have been suggested for the other minerals.

	SiO_2	TiO_2	ZrO_2	ThO_2	CeO_2	Ce_2O_3	Y_2O_3	Al_2O_3	Fe_2O_3	CaO
1. Johnstrupite	30.50	7.57	2.84	0.79	0.80	12.71[a]	1.11	1.52	0.50	27.76
2. Mosandrite	30.71	5.33	7.43	0.34	6.34	10.45[a]	3.52	—	0.56	22.53
3. Rinkite	29.08	13.36	—	—	—	21.25[a]	0.92	—	0.44[b]	23.26

	MgO	MnO	Na_2O	K_2O	H_2O	F				
1.	1.63	tr.	6.67	0.12	1.41	5.98	= 101.91	less O for F	2.50	= 99.41
2.	0.63	0.45	2.44	0.38	7.70	2.06	= 100.87	"	0.86	= 100.01
3.	—	—	8.98	—	—	5.82	= 103.11	"	2.45	= 100.66

[a] Incl. La_2O_3, Di_2O_3. [b] FeO.

Mosandrite is decomposed by hydrochloric acid, with separation of silica and the formation of a dark-red solution, which on heating gives off chlorine and becomes yellow. Rinkite is easily decomposed by dilute acids, with the separation of silica carrying titanium.

Monoclinic.—Johnstrupite, $a:b:c=1.6229:1:1.3911$, $\beta=86°\ 55\frac{3}{4}'$.

Rinkite $\begin{cases} a:b:5c=1.5688:1:1.4610, \beta=88°\ 47'. \\ a:b:c=1.5688:1:0.2922. \end{cases}$

Brögger shows that the three minerals of this group are all similar in angle to both zoisite and epidote. Des Cloizeaux had already pointed out the resemblance in form between mosandrite and zoisite.

Euhedral crystals of *johnstrupite* are prismatic parallel to the *c* axis and flattened parallel to *a*(100), the prism *f*(210) most prominent; also other prism faces of the third and second kinds (Fig. 1). Faces in prismatic zone striated parallel to *c* axis.

In *mosandrite* the crystals are long prisms parallel to the *c* axis,

flattened parallel to $a(100)$, but without terminal planes. Forms in prismatic zone the same as in johnstrupite, with nearly the same angles.

In *rinkite* the crystals are short prisms, or thick plates parallel to $a(100)$, with faces in the zone of c and of b axes as in johnstrupite (Fig. 2).

FIG. 1.

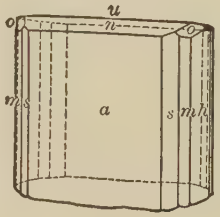


FIG. 2.

Twinning plane (100) often in polysynthetic lamellæ.

Cleavage parallel to (100) distinct. H. = 4, mosandrite; 5, rinkite. Sp. gr. = 2.93–3.03, mosandrite; 3.29, johnstrupite; 3.46, rinkite.

Optical Properties.—Optically positive (+); plane of the optic axes parallel to (010) in johnstrupite and mosandrite (Fig. 3), at right

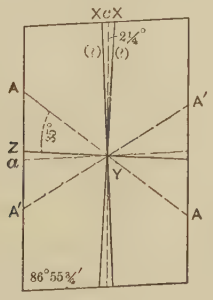


FIG. 3.

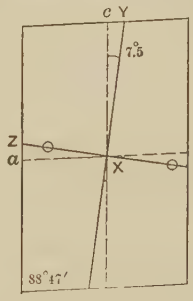


FIG. 4.

angles to (010) in rinkite (Fig. 4). In johnstrupite and mosandrite the acute bisectrix Z nearly normal to (100); X inclined $2\frac{1}{4}°$ to the c axis, whether in the acute or obtuse angle β is not known; dispersion of the bisectrices weak. Axial angle large and dispersion strong, $\rho > v$. In *johnstrupite*, $2E = 124°\ 40'$, $2V_r = 71°\ 10.5'$, $2V_y = 69°\ 54'$, $2V_{gr} = 68°\ 20'$, Brögger. Refraction low; according to Brögger, $\beta = 1.546$ (? 1.646).

In *mosandrite* from Låven, $2E = 128°\ 37'$, $2V_y = 74°\ 14'$, and $\alpha_y = 1.6455$, $\beta_y = 1.649$, $\gamma_y = 1.6577$, $\gamma_y - \alpha_y = 0.0122$ Wülfing.

In *rinkite* Y is inclined 7.5° to the c axis, probably in the acute angle β, for the acute bisectrix Z is apparently normal to (100), Lorenzen. Angle between the optic axes moderate; dispersion strong, $\rho < v$.

$2E_r = 73° 58'$, $2E_{bl} = 78° 6'$, Mallard.

$\alpha_r = 1.6595$, $\alpha_y = 1.6654$, $\alpha_{gr} = 1.6693$.

$\beta_r = 1.6627$, $\beta_y = 1.6682$, $\beta_{gr} = 1.6727$, $\beta_y - \alpha_y = 0.0028$, Osann.

Color in fresh *mosandrite* reddish brown, altering to dull greenish or yellowish brown; in *johnstrupite* brownish green. In thin section colorless to yellowish, with the pleochroism scarcely noticeable. In thick plates X very light yellow, Y light brownish yellow, Z light greenish yellow. In *rinkite* the color is yellowish brown to straw-yellow. Pleochroism in thick sections: X colorless, Y light yellowish white, Z yellow. Luster vitreous on cleavage surface to greasy or resinous elsewhere.

Occurrence.—Mosandrite and johnstrupite occur in nepheline-syenites and closely related rocks, chiefly in the region of the Langesund fjord, Norway; also in the aphanitic and lava equivalents in other localities. In the nepheline-syenite pegmatites it is often accompanied by fluorite, rosenbuschite, and (?) wöhlerite.

Rinkite occurs in large crystals in the nepheline-syenite at Kangerdluarsuk, Greenland; also in similar rocks of the Serra de Tinguá; and appears to be more widely distributed than mosandrite in other nepheline-syenites and their aphanitic equivalents. It is often intergrown with fluorspar and rosenbuschite, and accompanied by låvenite, astrophyllite, and (?) wöhlerite.

ASTROPHYLLITE.

$$(?)\overset{I}{R}_4\overset{II}{R}_4Ti(SiO_4)_4.$$

Chemical Composition.—Perhaps an orthosilicate in which $\overset{I}{R} = H$, Na,K, and $\overset{II}{R} = Fe,Mn$ chiefly, including also Fe_2O_3.

	SiO_2	TiO_2	ZrO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	
1. Brevik	33.23	7.09	4.97	4.00	3.75	23.58	9.90	1.27	1.13	2.51	5.82	
												ign. 1.86 = 99.11
2. Eikaholm	33.02	11.11	3.65	0.98	2.53	21.76	11.96	0.92	1.26	2.77	5.78	
												ign. 3.47, F 0.97 = 100.18
3. Colorado	34.68	13.58	2.20	0.70	6.56	26.10	3.48	0.30	—	2.54	5.01	
												ign. 3.54, CuO 0.42, Ta_2O_5 (?) 0.80 = 99.81

Specific gravity, (1) 3.324; (3) 3.375.

Decomposed by hydrochloric acid with separation of silica in scales.

Orthorhombic; $a:b:c=0.99025:1:4.7101$.

Euhedral crystals often elongated parallel to the c, or to the a, axis; flattened parallel to (010). Faces present $b(010)$, $g(038)$, $\beta(0.1.50)$, $i(434)$, and others (Fig. 1).

Anhedral crystals in long thin strips or blades, or in stellate groups.

Cleavage perfect parallel to (010) in brittle laminæ; very imperfect parallel to (001). Percussion figure on cleavage plates consists of two rays crossing at from 81° to 85°, nearly parallel to (014). H.=3. Sp. gr.=3.3–3.4.

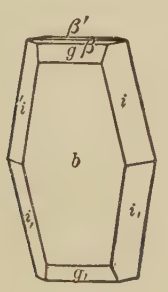


Fig. 1.

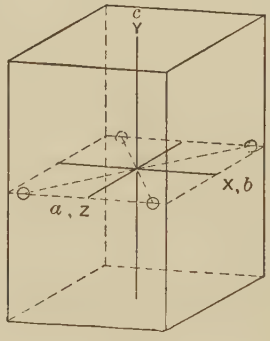


Fig. 2.

Optical Properties.—Optically positive (+); axial plane parallel to (001); acute bisectrix Z normal to (100), $X \parallel b$, $Y \parallel c$, $Z \parallel a$ (Fig. 2).

Angle between the optic axes large, $2E=160°$, Langesund, Brögger. $\rho > v$. Refraction and double refraction high.

Langesund, $\alpha_y=1.678$, $\beta_y=1.703$, $\gamma_y=1.733$, $\gamma_y-\alpha_y=0.055$, Lévy-Lacroix.

Color.—Bronze-yellow to gold-yellow; in thin section pleochroic, X deep orange-yellow, Y lemon-yellow, Z orange. Luster submetallic, pearly.

Occurrence.—Astrophyllite occurs in nephelite-syenite in the Langesund fjord, Norway; on the Kola Peninsula; at Kangerdluarsuk in Greenland, near Montreal, Canada; in pulaskite at Magnet Cove, Ark., in soda-granite with arfvedsonite at Peter's Dome, Pike's Peak; and elsewhere.

A mineral similar to astrophyllite in physical characters,—habit, cleavage, refraction and double refraction,—but different in the direction of absorption, $X=Y$ straw-yellow, Z gold-yellow, $Z>X=Y$, occurs in nephelite-syenites of Umptek and Lujavr Urt, Kola, and has been called *lamprophyllite* by Hackman.

TITANITE.

$CaSiTiO_5$.

Composition.—CaO, SiO_2, TiO_2=SiO_2 30.6, TiO_2 40.8, CaO 28.6 =100. Iron is present in varying amounts, sometimes manganese, also yttrium and cerium (eucolite-titanite).

Alteration.—Imperfectly soluble in hydrochloric acid. Titanite is known to undergo alteration in a number of different ways. It loses color and passes into a light-yellow, earthy mass accompanied by calcite. In other cases an opaque iron oxide is deposited along cleavage cracks. It also alters to rutile or anatase, and in phonolite of Klein-Priesen is replaced by a mixture of perovskite and calcite, with rutile and pyrite.

Monoclinic; $a:b:c=0.75467:1:0.85429$, $\beta=60°\ 17'$. Euhedral crystals very varied in habit, often wedge-shaped and flattened parallel to $c(001)$, with $m(110)$, $n(111)$, $t(\bar{1}11)$ (Fig. 1), also prismatic with

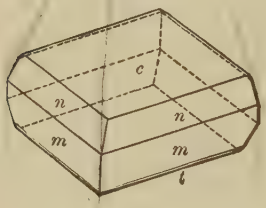


Fig. 1.

Fig. 2.

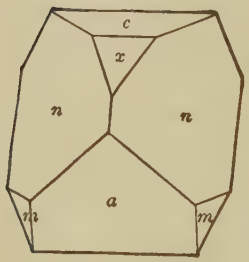


Fig. 3.

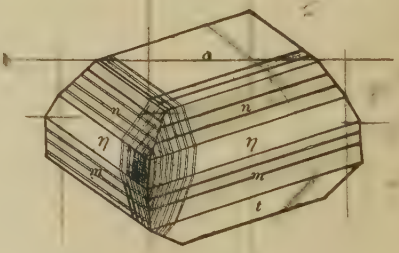


Fig. 4.

extension of $m(110)$ (Fig. 2), and less often in other directions with $a(100)$ and $x(102)$ (Fig. 3). In rocks the crystals are simple in habit, sections of crystals being commonly acutely rhombic, or lath-shaped with acute terminal edges. Also in irregularly shaped anhedrons.

Twinning.—(1) Twinning plane (100) rather common, contact twins, also cruciform penetration twins; (2) twinning plane (001) rather rare; (3) twinning plane approximately parallel to (221) in polysynthetic lamellæ as in Fig. 4.

Cleavage parallel to (110) rather distinct; parallel to (100) and ($\bar{1}12$) imperfect; in some varieties also parallel to (111) and ($\bar{1}11$). Parting parallel to the twinned lamellæ (221) often easy. H.=5–5.5. Sp. gr.=3.4–3.56.

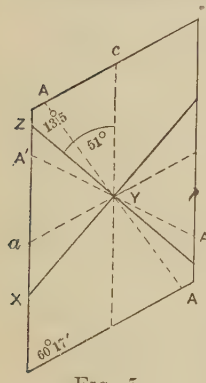


FIG. 5.

Optical Properties.—Optically positive (+); axial plane parallel to (010); acute bisectrix Z almost normal to $x(102)$, that is, $Z \wedge c = 51°$ in the obtuse angle β. Axial angle generally small, but variable; dispersion, $\rho > v$, very large. The optical constants of a large number of varieties of titanite have been determined by Busz, and may be found in Rosenbusch's Mikroskopische Physiographie, Vol. I, Part II, p. 295. Some of them are as follows:

St. Gothard	$2E_r = 57° 21'$	$2E_y = 52° 30'$	$2E_{gr} = 47° 55'$
"	$2V_r = 29° 30\frac{1}{2}'$	$2V_y = 27° \frac{1}{3}'$	$2V_{gr} = 24° 37\frac{1}{2}'$
Arendal	$2E_r = 78° 28'$	$2E_y = 71° 17'$	$2E_{gr} = 66° 24'$
Renfrew	$= 90° 57'$	$= 85° 59'$	$= 80° 18'$
Buoe (keilhauite)	$= 112° 31'$	$= 108° 35'$	$= 106° 37'$

St. Gothard	$\alpha_r = 1.8766$	$\beta_r = 1.8839$	$\gamma_r = 1.9987$	
"	$\alpha_y = 1.8874$	$\beta_y = 1.8940$	$\gamma_y = 2.0093$	$\gamma_y - \alpha_y = 0.1219$
"	$\alpha_{gr} = 1.8989$	$\beta_{gr} = 1.9041$	$\gamma_{gr} = 2.0232$	
Zillerthal	$\alpha_y = 1.9133$	$\beta_y = 1.9206$	$\gamma_y = 2.0536$	$\gamma_y - \alpha_y = 0.1403$
Wildkreuzjoch	$= 1.9042$	$= 1.9048$	$= 1.9171$	$= 0.0129$

$\gamma - \alpha = 0.1219$, $\gamma - \beta = 0.1153$, $\beta - \alpha = 0.0066$.

Refraction high; double refraction very high in some directions, but very low for sections nearly normal to the acute bisectrix Z, since $\beta - \alpha = 0.0066$. In thin sections the interference colors are gray of a very high order or of the lowest order. The low double refraction in the titanite from Wildkreuzjoch is abnormal.

Color.—Brown, gray, yellow, green, rose-red, and black. In thin section colorless, yellow, brownish, greenish, or reddish yellow. Pleochroism scarcely noticeable in thin section; in thicker sections or more strongly colored crystals:

	X	Y	Z
—	nearly colorless	yellow with green tint	orange to brownish red
Umptek	grayish white	light gray-brown	peachblow-red
Eucolite-titanite	nearly the same as Y	pale brownish yellow	light wine-yellow

Occurrence.—Titanite is widespread in igneous rocks of intermediate composition, in hornblende-granites, diorites, syenites, and nephelite-syenites, and in their aphanitic or porphyry equivalents. It is not commonly found in gabbro or basalt, or in peridotites, except when it occurs as leucoxene, an alteration-product of ilmenite or titaniferous iron oxide. Titanite also occurs in gneiss and schists, and in crystalline limestone, as in numerous localities in Canada and the United States.

Resemblances.—Titanite is usually well characterized by its crystal habit, color, high refraction and double refraction, and strong axial dispersion. But when anhedral it resembles anhedral crystals of rutile, xenotime, cassiterite, and hussakite when these are anomalously biaxial. They are then distinguishable by chemical means only.

Laboratory Production.—Titanite has been obtained from fusion of its constituents alone at 1400° C. (Van der Belleu); from molten silicate solutions in open crucibles. If the solution was low in silica, perovskite formed instead of titanite (Bourgeois). It has been formed in graphite crucibles by melting its constituents with charcoal at 1200° C. (Michel). It was first produced by Hautefeuille by fusing SiO_2 and TiO_2 with an excess of $CaCl_2$.

PEROVSKITE.

$CaTiO_3$.

Composition.—Calcium titanate, CaO 41.1, TiO_2 58.9 = 100. Iron is present in small amounts, replacing calcium. *Knopite* is a variety of perovskite in which the calcium is in part replaced by one of the cerium elements. Entirely decomposed by boiling sulphuric acid. Usually unaltered in igneous rocks, rarely changed to a greenish, strongly refracting aggregate, resembling leucoxene, which is TiO_2 and may possibly be anatase.

Crystal Form.—Isometric system. Euhedral crystals in igneous rocks are generally octahedrons modified by the dodecahedron and cube. In the crystalline schists they are cubes often highly modified. Anhedral crystals rare.

Twinning on octahedral face in the form of interpenetrated cubes.

Cleavage parallel to (100) rather perfect. In thin section noticeable only in the larger individuals. Fracture uneven to subconchoidal. H. = 5.5. Sp. gr. = 4.017 Achmatovsk, 4.03–4.039 Zermatt, 4.11–4.29, knopite, Alnö.

Optical Properties.—Isotropic in microscopic crystals. Anomalous double refraction in larger crystals with lamellar structure, the cause of which has not been satisfactorily explained. Index of refraction high, $n_Y = 2.38$ Des Cloizeaux; therefore the marginal shadow due to total reflection is strong.

Color.—Pale yellow, orange-yellow, reddish brown, grayish black, in incident light; grayish white, violet-gray, brownish to reddish, rarely greenish, in transmitted light. Zonal arrangement of colors sometimes present. Luster adamantine to metallic-adamantine.

Modes of Occurrence.—Perovskite occurs in basic igneous rocks, peridotite, melilite-basalt, alnöite, and in nephelite- and leucite-bearing rocks, that is, in titaniferous rocks low or comparatively low in silica. It also occurs to some extent in crystalline schists; in pyroxene-gneiss; in chlorite slate at Achmatovsk in the Ural; in talcose schist in the valley of Zermatt; in crystalline limestone at Schelingen, on the Kaiserstuhl. *Knopite* occurs in the crystalline limestone of Långörsholmen, in the northern part of Alnö. Perovskite has been noted as an alteration-product of titanite in phonolite at Klein-Priesen, Bohemia.

Resemblances.—Perovskite when nearly opaque resembles hematite and ilmenite; when transparent it is like chromite, picotite, and melanite. It also resembles dysanalyte, pyrochlore, pyrrhite, and koppite. From hematite and ilmenite it is distinguished by its insolubility in hydrochloric acid. From the other minerals it is distinguished by chemical tests for the characteristic constituents in each case.

Laboratory Production.—Perovskite has been formed in a variety of ways; by fusing limestone and an alkali silicotitanate, or a mixture of lime, titanium oxide, with alkali carbonate at a high temperature until the alkali is driven off. The crystals were octahedral and double-refracting (Ebelmen). It has also been produced by fusing the constituents of perovskite in basic silicates or a silicate rock and cooling very slowly. When the silicate solution is too siliceous, titanite forms in place of perovskite. The crystals were octahedrons and aggregates and were irregularly doubly refracting (Bourgeois). It has also been formed by the action of a stream of moist air or carbon dioxide with hydrochloric acid vapor upon a flux of titanium oxide, silica, and calcium chloride (Hautefeuille).

DYSANALYTE.

$6(Ca,Fe)TiO_3 \cdot (Ca,Fe)Nb_2O_6$.

A titanoniobate of calcium and iron, with small amounts of other constituents, as shown in the following analyses:

	TiO_2	Nb_2O_5	Ta_2O_5	Y_2O_3*	Fe_2O_3	FeO	Ce_2O_3†	CaO	MnO	
Dysanalyte, Kaiserstuhl	41.47	23.23	—	5.42	—	5.81	5.72	19.77	0.43	
										Na_2O 3.57 = 100.00
										MgO
" Magnet Cove	44.12	4.38	5.08	—	5.66	—	0.10	33.22	0.74	
										SiO_2 0.08, magnetite 0.73 = 99.53

* Yttrium earths. † Cerium oxides.

It is isomorphous with perovskite, and crystallizes in cubes, with cubic cleavages. H. = 5–6. Sp. gr. = 4.13. Opaque, iron-black. Luster submetallic.

Dysanalyte occurs in granular limestone of Vogtsburg, on the Kaiserstuhl, Baden.

A related mineral with much less niobium and tantalum, having more nearly the composition of perovskite, is found with magnetite, brookite, rutile, etc., in the region of nephelite rocks at Magnet Cove, Ark.

PYROCHLORE GROUP.

Pyrochlore, $RNb_2O_6 \cdot R(Ti,Th)O_3 \cdot NaF$.
Koppite, $R_2Nb_2O_7 \cdot \frac{2}{5}NaF$.
Microlite, $Ca_2Ta_2O_7 \cdot$ pt.
(Pyrrhite.)

Chemical Composition.—*Pyrochlore* is chiefly a niobate of the cerium metals, calcium, and other bases, with also titanium, thorium, fluorine. The part played by fluorine in the minerals of this group is doubtful. *Koppite* is essentially a pyroniobate of cerium, calcium, etc. *Microlite* is essentially a calcium pyrotantalate, $Ca_2Ta_2O_7$, but containing niobium, fluorine, and a variety of bases in small amounts. *Pyrrhite* is a niobate related to pyrochlore and probably identical

with microlite. For the chemical analyses of these rare minerals see Dana's System of Mineralogy, 6th edition.

Crystal Form.—Isometric system. Euhedral crystals octahedrons in pyrochlore, microlite, and pyrrhite; dodecahedrons in koppite. Crystals generally very small; sometimes in anhedral grains.

Cleavage in pyrochlore octahedral, sometimes distinct, not developed in the other members of the group. Fracture conchoidal. H.=5–5.5. Sp.gr.=4.2–4.36 in pyrochlore; 4.45–4.56 in koppite; 5.485–5.562 in microlite; 4.1–4.3 in pyrrhite.

Optical Properties.—Isotropic when transparent; pyrochlore sometimes faintly doubly refracting. Transparent to opaque. *Pyrochlore* is brown, reddish to blackish brown; in transmitted light, brown, red; crystals translucent to opaque. *Koppite* is brown; by transmitted light red; transparent. *Microlite* is pale yellow to brown, rarely hyacinth-red; transparent to translucent or nearly opaque. *Pyrrhite* is hyacinth-red by incident light, orange-yellow to red in transmitted light. Luster vitreous to resinous.

Modes of Occurrence.—*Pyrochlore* occurs in nephelite-syenite of Ditro and Miask in the Ural, also in nephelite-syenite at Fredriksvärn and Laurvik, and other localities in Norway. It occurs in the syenite of Peter's Dome, Pike's Peak, Colo., also in an alkalic granite in Madagascar. It has been developed in crystalline limestone on Alnö, where it exhibits brown and yellow zones and spots. *Koppite* is found in crystalline limestone as a product of contact metamorphism at Schelingen, on the Kaiserstuhl. *Microlite* occurs in pegmatite veins, as at Chesterfield, Mass., in albite with tourmaline, spodumene, and columbite; similarly associated in the pegmatite of Branchville, Conn., and at Utö, Sweden; in a mica pegmatite at Amelia Court House, Va., and in granitic veins on Elba. *Pyrrhite* occurs in sanidinites on San Miguel, Azores, and at Laacher See. It is also found in drusy feldspar cavities with lepidolite, albite, and topaz at Alabashka, near Mursinka, in the Ural.

Resemblances.—These minerals are most like perovskite, dysanalyte, chromite, picotite, and melanite, from which they are distinguished chiefly by chemical means.

CALCITE GROUP.

RCO_3.

Calcite, $CaCO_3$.
Dolomite, $(Ca,Mg)CO_3$.
Ankerite, $CaCO_3 \cdot (Mg, Fe)CO_3$.
Magnesite, $MgCO_3$.
Breunnerite, $(Mg,Fe)CO_3$.
Siderite, $FeCO_3$.
Rhodochrosite, $MnCO_3$.
Smithsonite, $ZnCO_3$.

Chemical Composition.—Carbonates of calcium, magnesium, iron, or manganese, also zinc, singly or in various proportions. But the zinc carbonate is more of a vein mineral than a rock-making one.

Calcite, CO_2 44.0, CaO 56.0 = 100, is often wholly calcium carbonate, but may contain traces or small amounts of the other metals, especially magnesium. *Dolomite* is normally $CaCO_3 \cdot MgCO_3 = CO_2$ 47.8, CaO 30.4, MgO 21.8 = 100, but the proportion of Ca : Mg varies from 1 : 1. Small amounts of the elements may also be present. *Ankerite* or brown spar is an iron-bearing dolomite. Normal ankerite is $2CaCO_3 \cdot MgCO_3 \cdot FeCO_3$, but the proportions of iron and magnesium vary considerably. *Magnesite* when pure is CO_2 52.4, MgO 47.6 = 100. Iron is often present, forming transitions through *breunnerite* and *mesitite*, $2MgCO_3 \cdot FeCO_3$, to *siderite*, CO_2 37.9, FeO 62.1 = 100. Manganese, calcium, and magnesium may be present in small amounts. *Rhodochrosite*, CO_2 38.3, FeO 61.7 = 100. The other metals may be present. *Smithsonite*, CO_2 35.2, ZnO 64.8 = 100. In addition to the other metals, cadmium is present in rare instances. All minerals of this group dissolve in hydrochloric acid with effervescence, but some more readily than others. Since some of the chemical reactions of the different minerals of this group are often necessary tests for distinguishing them from one another, they will be described under the section treating of resemblances.

Alteration.—The carbonates are liable to solution, and the ferrous iron may be oxidized to hematite or hydrous ferric oxides, goethite, limonite, etc. They may be altered by silication through contact metamorphism, and other modes of metamorphism, to the many silicate minerals having Ca, Mg, Fe, Mn, as bases, and known to

replace the carbonates in the crystalline schists and in zones of contact metamorphism, or in blocks inclosed in lavas.

Trigonal System.—Scalenohedral class, except in the case of dolomite, which crystallizes in the rhombohedral class (tri-rhombohedral, Dana). The isomorphism of the series is shown in the axial ratios and the angle between the faces of the unit rhombohedron $r(10\bar{1}1)$.

	c	rr'
Calcite	0.8543	74° 55′
Dolomite	0.8322	73° 45′
Ankerite	0.8332	73° 48′
Magnesite	0.8112	72° 36′
Siderite	0.8184	73° 0′
Rhodochrosite	0.8184	73° 0′
Smithsonite	0.8063	72° 20′

Euhedral crystals of calcite are of many different habits and are often highly modified; those of the other minerals are less common and less highly developed. But as constituents of rocks the forms are very simple and seldom euhedral.

Fig. 1.

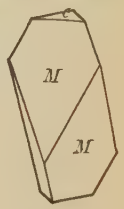


Fig. 2.

Calcite as a rock constituent is almost never euhedral, except when crystallized on the walls of cavities. In rare instances it occurs as a simple unit rhombohedron $r(10\bar{1}1)$ (Fig. 1). It is usually anhedral, its outline determined by that of adjacent minerals. In granular limestones it is in irregularly shaped anhedrons. It is sometimes in prismatic or fibrous aggregates; sometimes lamellar in form.

Dolomite and *ankerite* occur in simple rhombohedrons $r(10\bar{1}1)$, less often in steep rhombohedrons $M(40\bar{4}1)$, with the base $c(0001)$ (Fig. 2) and sometimes with $r(10\bar{1}1)$ subordinate. Such euhedral crystals occur in some quartz-schists and in anhydrite and gypsum. Anhedral crystals are like those of calcite.

Magnesite and *breunnerite* sometimes occur in euhedral crystals as unit rhombohedrons $(10\bar{1}1)$, or in steep ones, in talcose schist and serpentine. Anhedral crystals are the more common form.

Siderite and *rhodochrosite* usually occur in anhedral crystals as rock constituents; euhedral crystals forming chiefly on the walls of cavities. *Smithsonite* is seldom a rock constituent, but occurs as incrustations, or filling cavities and cracks.

Twinning.—Common in calcite, dolomite, ankerite, and siderite. (1) Twinning plane and composition plane $(01\bar{1}\bar{2})$, the c axes inclined 52° 30½′; very common and often repeated polysynthetically, producing thin lamellæ. This is a gliding plane, and the twinning may be produced easily by pressure. Since there are three planes of this character equally capable of becoming gliding or twinning planes, twinned lamellæ of this kind may intersect one another in one crystal. (2) Twinning and composition plane the basal pinacoid (0001). The c axes parallel in the twinned parts; not recognizable optically in thin section, but by the reversed cleavage in the twinned parts. This is common. Other modes of twinning known to occur on euhedral crystals of calcite have not been recognized on the rock-making carbonates.

Cleavage parallel to the unit rhombohedron $(10\bar{1}1)$ highly perfect in all minerals of this group. Parting parallel to the gliding plane $(01\bar{1}2)$ in those minerals twinned on this plane. A parting parallel to $(11\bar{2}0)$ in calcite is rare. Fracture conchoidal, obtained with difficulty owing to the perfect cleavage in three directions.

Hardness varies with the composition, and in calcite with the direction in which it is tested on the crystal.

	H.	Sp. gr.
Calcite	3	2.713–2.723 on pure crystals
Dolomite	3.5–4	2.8 –2.9
Ankerite	3.5–4	2.95 –3.1
Magnesite	3.5–4.5	3.0 –3.12
Siderite	3.5–4	3.83 –3.88
Rhodochrosite	3.5–4.5	3.45 –3.60
Smithsonite	5	4.30 –4.45

Optical Properties.—Optically negative (−). Double refraction very strong, usually exhibiting in thin section interference colors of a very high order, appearing yellowish or pearl-gray between crossed nicols. Only yielding colors of the second or third orders in extremely thin films, less than 0.01 mm. thick. The indices of refraction vary greatly in different positions of a crystal section, the lowest being lower than that of Canada balsam for calcite, dolomite, and magnesite, but considerably higher for siderite, while the highest index of refraction is high as compared with that of balsam. This causes a marked change of appearance in the shadows of cracks and in the shagreened surface of a section of calcite, dolomite, and magnesite. The shadows and apparent relief seen when polarized light is vibrating parallel to the slower ray ω, disappear when the section is rotated 90° and the light vibrates parallel to the faster ray, ε.

	ω_y	ϵ_y	$\omega_y - \epsilon_y$	
Calcite	1.65849	1.48625	0.17224	Schrauf
Dolomite	1.68174	1.50256	0.17918	Des Cloizeaux
" 1.92 $FeCO_3$ Greiner	1.6830	1.5034	0.1796	Eisentruth
" 3.29 " "	1.6883	1.5070	0.1833	"
" 10.76 " "	1.6983	1.5133	0.1850	"
" 10.61 " * "	1.7005	1.5148	0.1857	"
Magnesite	1.717	1.515	0.202	Mallard
Breunnerite, Greiner †	1.7174	1.5285	0.1889	Eisentruth
Siderite, Camborne ‡	1.8724	1.6338	0.2386	Hutchinson
" Wolfsberg §	1.9341	1.6219	0.3122	Ortloff

* $CaCO_3$, 18.71; $MgCO_3$, 30.47; $FeCO_3$, 10.61; $MnCO_3$, 37.93.
† $CaCO_3$, 1.29; $MgCO_3$, 65.78; $FeCO_3$, 16.33; $MnCO_3$, 12.83.
‡ $CaCO_3$, 0.18; $MgCO_3$, 0.26; $FeCO_3$, 98.43; $MnCO_3$, 1.82.
§ $CaCO_3$, 0.86; $MgCO_3$, 5.42; $FeCO_3$, 77.32; $MnCO_3$, 17.04.

Sections of radially fibrous spherulites of calcite when viewed with a low-power lens focussed for the point of convergence of the transmitted rays exhibit interference crosses and rings.

Color.—*Calcite:* colorless or white; also various pale shades of gray, red, green, blue, violet, yellow; also brown and black when impure. In thin section colorless, grayish, yellowish, brownish. *Dolomite:* colorless, white, reddish or greenish white; also rose-red, green, brown, gray, and black. In thin section colorless or pale shades of the colors named. *Magnesite:* white, yellowish or grayish white, brown. *Siderite:* ash-gray, yellowish or greenish gray, brown, brownish red, rarely green. In thin section pale shades of these colors, or colorless. *Rhodochrosite:* shades of rose-red, yellowish gray, fawn-colored, dark red, brown. *Smithsonite:* white, grayish, greenish, brownish white, sometimes green, blue, brown. Luster vitreous to pearly.

Occurrence.—The carbonates occur as secondary minerals in all kinds of rocks, calcite and dolomite being the most widespread and abundant; magnesite and siderite and the intermediate varieties less so. Calcite is considered to be primary in certain phanerocrystalline igneous rocks. Owing to the optical resemblance between the carbonates, they have not been distinguished from one another in rock sections in most instances, but have generally been called calcite without special identification.

Calcite and *dolomite* are widespread in sedimentary rocks, chiefly forming crystalline limestones and marble; in beds and masses in the crystalline schists; as constituents of certain schists; as infiltrations in cavities and fissures in igneous rock; and as products of the alteration of silicates and other minerals.

Dolomite is said to be less often twinned polysynthetically parallel to $(01\bar{1}2)$ than calcite (Inostranzeff) and to be more often twinned on $(02\bar{2}1)$. In crystalline limestone at Kandy and Matala, Ceylon, dolomite and calcite are sometimes interlaminated with one another on the basal plane (0001), which appears in the weathering, the dolomite being less soluble. Sometimes the two are graphically intergrown, the calcite serving as the matrix crystal.

Dolomite and *magnesite* occur in euhedral crystals in some talc-schists and chlorite-schists, and in certain phyllites. Dolomite occurs in anhydrite and gypsum, and magnesite more commonly in altered magnesian rocks, and is frequently associated with serpentine, talc, and steatite rocks.

Siderite occurs in stratified deposits, and to some extent in the crystalline schists. It is less frequently an alteration-product in the more ferruginous igneous rocks.

Rhodochrosite is rare as a rock-making mineral, but occurs in crystalline limestone with franklinite at Franklin Furnace, N. J. It is found in slates at Placentia Bay, Newfoundland. It occurs in a vein of albitic granite at Branchville, Conn. *Smithsonite* is formed in calcareous rocks, usually in veins, sometimes as beds.

Resemblances.—The members of the calcite group occurring as rock constituents are distinguished from other rock-making minerals by the combination of their pronounced rhombohedral cleavage, strong double refraction, and optically negative character. But they resemble one another so closely and grade into one another to such an extent that they are equally difficult to distinguish from one another, except by chemical means. Siderite is distinguished by its higher refraction, the lowest index of refraction being higher than that of Canada balsam or even than that of actinolite or wollastonite.

The chief distinctions between calcite and dolomite rest upon their behavior toward acids. Calcite effervesces in cold dilute hydrochloric acid, and in acetic acid vigorously. Dolomite is acted on only slightly in cold acids, but vigorously when these reagents are heated. Dolomite and strongly magnesian calcite are distinguishable from calcite with little or no magnesia by their action toward a solution of ammonium phosphate in dilute acetic acid. Decomposition quickly ceases on crystals with more than 12 per cent. of $MgCO_3$, because of the coating of magnesium phosphate which is deposited over the exposed surface. A similar difference of behavior is recognizable when a 10 per cent. solution of aluminium chloride is used.

Dolomite is very slowly acted upon. *Magnesite* is not acted on by cold hydrochloric acid.

Laboratory Production.—Crystals of *calcite* have been obtained by heating calcium carbonate (chalk) in a closed vessel (James Hall). Much work has been done on the crystallization of calcite and aragonite from solutions. From sea-water in which calcium was in the form of bicarbonate, calcite was deposited by evaporation at ordinary temperatures; aragonite was formed upon heating (Link). According to H. Worth, it is not the temperature that controls the crystallization of calcite and aragonite, but the alkaline or acid condition of the solution. Calcite crystallizes from an acid solution, aragonite from an alkaline one. Calcite has been obtained from fused alkali carbonates (Rose), and from fused alkali chlorides in skeleton crystals like those of snow (Bourgeois). *Dolomite* has been obtained by the action of a solution of magnesium bicarbonate on calcium carbonate at 100° in a closed tube (Hoppe-Seyler). *Magnesite* has been produced in a closed tube at 160° by the action of magnesium sulphate and sodium carbonate, or of magnesium chloride and sodium bicarbonate (Senarmont).

ARAGONITE.

$CaCO_3$.

Calcium carbonate, CO_2 44.0, CaO 56.0 = 100. Some varieties contain a little strontium, others lead and rarely zinc. Dissolves in acid with effervescence like calcite.

Orthorhombic; $a:b:c = 0.622444:1:0.720560$. Euhedral crystals commonly acicular, also in short pseudohexagonal prisms which are penetration twins. More common forms present $m(110)$, $b(010)$, $k(011)$, $p(111)$, $s(121)$, $c(001)$, and steep bipyramids and prisms of the first kind. Crystals often in stellate groups. Also globular, fibrous, compact aphanitic.

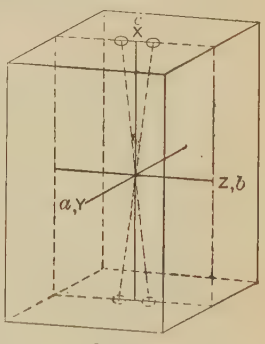


Fig. 1.

Twinning and composition plane (110), both contact and penetration twins, and in polysynthetic lamellæ.

Cleavage parallel (010) distinct; also parallel to (110); parallel to (011) imperfect. Fracture subconchoidal. H. = 3.5–4. Sp. gr. = 2.93 2.95.

Optical Properties.—Optically negative (−); plane of the optic axes parallel to (100); acute bisectrix X normal to (001), $X \parallel c$,

$Y \parallel a$, $Z \parallel b$. Axial angle small $2V_y = 18° 11'$, dispersion weak, $\rho < v$, Kirchoff. Double refraction very strong; indices of refraction lower than that of Canada balsam and much higher, as in calcite.

$\alpha_y = 1.53013$ $\beta_y = 1.68157$ $\gamma_y = 1.68589$ $\gamma_y - \alpha_y = 0.15576$ Radberg
$= 1.5295$ $= 1.6805$ $= 1.6848$ $= 0.1553$ Melczer

Color.—Colorless, white, gray, yellow, green, and violet. In thin section colorless. Luster vitreous, inclining to resinous on surface of fracture.

Occurrence.—Aragonite as a rock constituent occurs only as an alteration-product in basic eruptive rocks, usually crystallized in cavities or cracks or in basaltic tuffs.

The pisolite of Carlsbad, Bohemia, and of Hammam-Meskutin, Algeria, which has been considered to be aragonite, has been found to be forms of calcium carbonate called *ktypeite* by Lacroix. It is characterized by low Sp. gr. = 2.58–2.70, low double refraction = 0.020 approx., and optically positive (+) character. It behaves in part uniaxial, in part biaxial with $2E = 50°$ approx. Upon heating to near red heat the concretions decrepitate violently, and after continued heating become calcite. Other pisolites appear to be optically positive in thin section.

Laboratory Production.—The production of aragonite is noted in connection with that of calcite.

HYDROMAGNESITE.

$3MgCO_3 \cdot Mg(OH)_2 + 3H_2O$.

Basic magnesium carbonate, $4MgO \cdot 3CO_2 \cdot 4H_2O = CO_2$ 36.3, MgO 43.9, H_2O 19.8 = 100. Soluble in acids; crystalline compact varieties dissolve with effervescence in hot acid.

Orthorhombic; $a:b:c = 1.0379:1:0.4652$. Euhedral crystals bounded by (100), (110), and (121). Usually acicular or bladed, and tufted; also massive, chalky or mealy.

Cleavage not recognizable. H. = 3.5 on crystals. Sp. gr. = 2.145–2.18.

Optical Properties.—Optical normal Y parallel to the length of the prism. Refraction low, between that of Canada balsam, 1.539, and that of the ordinary ray of calcite, 1.658; double refraction very weak.

Color.—White to grayish and yellowish. In thin section colorless Luster vitreous to silky or subpearly, also earthy.

Occurrence.—Hydromagnesite occurs chiefly in serpentine as a secondary mineral, sometimes accompanying and resulting from the alteration of brucite and of periclase. It has been found at Hrubschitz, Moravia; at Kaiserstuhl, Baden; at Hoboken, N. J., and near Texas, Pa.

ANHYDRITE.

$CaSO_4$.

Calcium sulphate. SO_3 58.8, CaO 41.2 = 100. Soluble in hydrochloric acid. Alters to gypsum by absorbing moisture.

Orthorhombic; $a:b:c = 0.89325:1:1.0008$. Euhedral crystals not common. Usually anhedral, in rather large cleavable crystals; also fibrous, lamellar, granular.

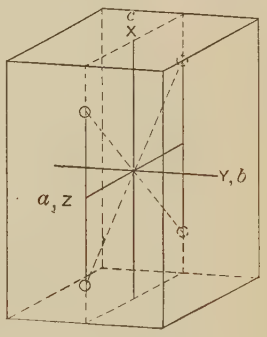


Fig. 1.

Twinning.—(1) Plane (012); (2) plane (101) sometimes in polysynthetic lamellæ, which may be developed by heat (Mügge).

Cleavage parallel to the three pinacoids, but with different degrees of perfection: parallel to (001) very perfect; parallel to (010) also perfect; parallel to (100) somewhat less so; resembling cubical cleavage. Fracture uneven, somewhat splintery. H. = 3–3.5. Sp. gr. = 2.899–2.956.

Optical Properties.—Optically positive (+); plane of the optic axes parallel to (010); acute bisectrix Z normal to (100); $X \parallel c$, $Y \parallel b$, $Z \parallel a$ (Fig. 1). Axial angle large; dispersion noticeable, $\rho < v$.

Berchtesgaden	$2E_r = 70° 53'$	$2E_y = 71° 39'$	$2E_{gr} = 72° 6'$	Zimanyi
	$2E_r = 70° 18'$		$2E_v = 72° 42'$	Grailich
	$2E = 71° 24'$–$42'$			Des Cloizeaux

Refraction moderate, double refraction high:

Stassfurt	$\alpha_y = 1.5693$	$\beta_y = 1.5752$	$\gamma_y = 1.6130$	$\gamma_y - \alpha_y = 0.0437$	Mühlheims
Hallein	$= 1.5696$	$= 1.5755$	$= 1.6136$	$= 0.0440$	Danker
Berchtesgaden	$= 1.5700$	$= 1.5757$	$= 1.6138$	$= 0.0438$	Zimanyi

Color.—White, grayish, bluish, reddish, brick-red. In thin section colorless. Luster on (001) pearly; on (100) somewhat greasy; on (010) vitreous.

Occurrence.—Anhydrite occurs with limestone associated with gypsum, and also with beds of rock-salt, at various localities in Europe and America.

Resemblances.—Anhydrite is well characterized by its cleavage and optical properties, and is not likely to be confused with any other mineral with which it may be associated.

Laboratory Production.—Anhydrite has been obtained from gypsum by heating it in a closed vessel with sodium or calcium chloride (Hoppe-Seyler); also at a red heat from a solution in the chlorides of potassium, sodium, etc. It has been produced by diffusion of a solution of magnesium sulphate and calcium chloride in a saturated solution of potassium and sodium chlorides (Brauns).

GYPSUM.

$CaSO_4 + 2H_2O$.

Hydrous calcium sulphate. SO_3 46.6, CaO 32.5, H_2O 20.9 = 100. Soluble in hydrochloric acid, and also in 400 to 500 parts of water.

Monoclinic; $a:b:c = 0.68994:1:0.41241$, $\beta = 80° \ 42\frac{1}{6}'$. Euhedral crystals usually simple in habit, commonly flattened parallel to $b(010)$, with $m(110)$, $l(111)$, and sometimes $e(\bar{1}03)$ (Figs. 1, 2). Sometimes prismatic in the direction of the c axis, sometimes by the development of $l(111)$, and of other forms. Also somewhat rounded, lenticular, or warped. Anhedral crystals in foliated masses; lamellar stellate; fibrous; granular.

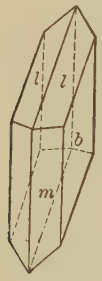


Fig. 1.

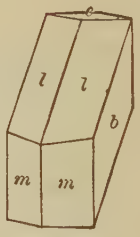


Fig. 2.

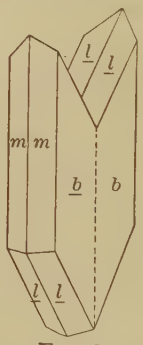


Fig. 3.

Twinning plane and composition plane (100) (Fig. 3), also cruciform penetration twins; sometimes twinning and composition plane (101), less common.

Cleavage parallel to (010) eminent, yielding folia; parallel to (100) giving a conchoidal surface; parallel to ($\bar{1}11$) with a fibrous surface. gliding planes parallel to ($\bar{1}03$) and ($\bar{5}09$). H.= 1.5–2. Sp. gr.=2.314–2.328.

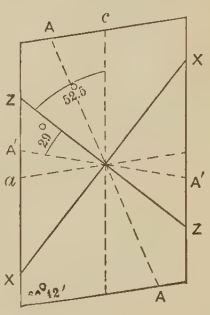


FIG. 4.

Optical Properties.—Optically positive (+). Plane of the optic axes parallel to (010) at ordinary temperatures (Fig. 4); with rise of temperature the angle of the optic axes decreases, becoming 0° for red at 116°; above this the angle opens in the plane perpendicular to (010). The acute bisectrix Z is inclined 52½° to the c axis in the obtuse angle β, and is noticeably dispersed. $Z_r \wedge Z_{bl} = 0°\ 30'$. Axial angle large; dispersion strong, $\rho > v$, inclined.

$2V_r = 57°\ 18'$	$2V_y = 58°\ 8'$	$2V_{gr} = 58°\ 6'$	Lang
$= 57°\ 28'$	$= 58°\ 1.5'$	$= 57°\ 56'$	Dufet

Refraction and double refraction low;

—	$\alpha_y = 1.5208$	$\beta_y = 1.5229$	$\gamma_y = 1.5305$	$\gamma - \alpha = 0.0097$	Lang
Sicily	$= 1.5204$	$= 1.5229$	$= 1.5296$	$= 0.0092$	Klein
Romagna	$= 1.5204$	$= 1.5225$	$= 1.5296$	$= 0.0092$	Viola
Montmartre	$= 1.5205$	$= 1.5226$	$= 1.5296$	$= 0.0091$	Dufet

Color.—Colorless, white; sometimes gray, flesh-red, yellow, blue; impure varieties often black, brown, red, or reddish brown. In thin section colorless. Luster on (010) pearly and shining, other faces subvitreous. Massive varieties often glistening, sometimes dull earthy.

Occurrence.—Gypsum forms deposits in sedimentary rocks, especially in association with limestones, marls, and clays. When it composes the whole mass its crystals are anhedral, but when there is a considerable amount of clay or other material present they are euhedral. It is frequently associated with anhydrite and rock-salt. It also occurs in the vicinity of volcanic vents about fumaroles.

ALUNITE.

$$K(AlO_2H_2)_3(SO_4)_2.$$

Hydrous sulphate of aluminium and potassium, $K_2O \cdot 3Al_2O_3 \cdot 4SO_3 \cdot 6H_2O = SO_3$ 38.6, Al_2O_3 37.0, K_2O 11.4, H_2O 13.0 = 100. Soluble in sulphuric acid.

Trigonal; scalenohedral class. $c = 1.2520$. Euhedral crystals rhombohedrons $r(10\bar{1}1)$ resembling cubes ($rr' = 90°\ 50'$) modified by

other rhombohedrons; also tabular parallel to $c(0001)$. Anhedral crystals massive, with lamellar fibrous, granular, or aphanitic texture.

Cleavage parallel to (0001) distinct; parallel to $(10\bar{1}1)$ in traces. Fracture flat, conchoidal, uneven; also splintery and earthy. H. = 3.5 –4. Sp. gr. = 2.58–2.752.

Optical Properties.—Optically positive (+). Refraction low, double refraction rather strong.

Tolfa, $\omega = 1.572$, $\varepsilon = 1.592$, $\varepsilon - \omega = 0.020$, Lévy-Lacroix

Color.—White, sometimes grayish or reddish. In thin section colorless. Luster vitreous; on basal plane somewhat pearly.

Occurrence.—Alunite is a secondary mineral in feldspathic rocks altered by means of sulphurous vapors. It occurs in altered rhyolites, dacites, trachytes, and andesites; at Rosita Hills, Colo., in andesite; with hyalite and opal at Queretaro, Mexico; with opal on Santorin, and in other localities in the Grecian Archipelago, and elsewhere in Europe.

Resemblances.—Alunite is similar to brucite in refraction, double refraction, and cleavage, and can only be distinguished by its hardness and chemical reactions. It is somewhat like the scapolites in refraction, but differs from them in double refraction and optical character. It is near quartz in refraction, but differs from it in double refraction and cleavage.

APATITE.

$(Ca(F,Cl))Ca_4(PO_4)_3$.

Chemical Composition.—$(3CaO{\cdot}P_2O_5)_3 + CaF_2$, and $(3CaO{\cdot}P_2O_5)_3 + CaCl_2$. Besides fluor-apatite and chlor-apatite there are intermediate compounds containing both fluorine and chlorine.

Fluor-apatite, P_2O_5 42.3, CaO 55.5, F 3.8 = 101.6.

Chlor-apatite, P_2O_5 41.0, CaO 53.8, Cl 6.8 = 101.6.

Some apatites contain the hydroxyl (OH), others a considerable amount of Mn; also traces of Di, Ce, La. One occurrence of apatite in the syenite of Norway contained 5 per cent. of cerium oxide.

Alteration.—Apatite is soluble in hydrochloric and nitric acid. It does not appear in an altered condition in rock sections, but is always fresh and appears to be one of the last minerals to undergo decomposition.

Hexagonal. Bipyramidal class. $c = 0.734603$. Euhedral crystals commonly prisms with $m(10\bar{1}0)$, rarely $a(11\bar{2}0)$, and the bipyramid $x(10\bar{1}1)$, less often $(10\bar{1}2)$, and the basal pinacoid $c(0001)$ (Figs. 1, 2);

also bipyramids of the third kind. Crystals often highly modified. In the rock mass apatite crystals are usually in simple forms, as in the figures 1 and 2, and vary from short prisms, 2 or 3 times longer than thick, to long, thin needles or hair-like prisms 300 times the width in length. Anhedral crystals, rounded or irregularly shaped, are common in the coarser-grained rocks; also fibrous, concretionary, and earthy. Different names have been given to apatite in various states

Fig. 1.

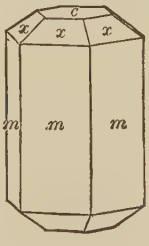


Fig. 2.

of aggregation, as *phosphorite* when fibrous concretionary, *osteolite* when earthy.

Cleavage parallel to (0001) imperfect; that parallel to $(10\bar{1}0)$ more so, but not generally noticeable in microscopic crystals. Fracture conchoidal and uneven. H.=5, sometimes 4.5 when massive. Sp. gr.=3.17–3.23.

Optical Properties.—Optically negative (−). Sometimes anomalously biaxial in large crystals that have grown in cavities. Refraction moderately high, double refraction weak.

Fluor-apatite, Minot, Me.	$\omega_r=1.6307$	$\varepsilon_r=1.6287$	$\omega_r-\varepsilon_r=0.0020$ Wolff-Palache
" " "	$\omega_y=1.6335$	$\varepsilon_y=1.6316$	$\omega_y-\varepsilon_y=0.0019$ Wolff-Palache
Apatite, Sulzbachthal	=1.6355	=1.6329	=0.0026 Zimanyi
Fluor-apatite, Sondalo Veltlin	=1.6379	=1.6349	=0.0030 Brugnatelli
" Jumilla	=1.637	=1.633	=0.004 Zimanyi
" "	=1.6381	=1.6345	=0.0036 Hlawatsch
" "	$\omega_{gr}=1.6410$	$\varepsilon_{gr}=1.6376$	$\omega_{gr}-\varepsilon_{gr}=0.0034$ Hlawatsch
" "	$\omega_y=1.6388$	$\varepsilon_y=1.6346$	$\omega_y-\varepsilon^y=0.0042$ Lattermann
Apatite, Cappucini di Albano	=1.6391	=1.6341	=0.0050 Zambonini
" Tyrol	=1.6449	=1.6405	=0.0034 Zimanyi

Color.—Sea-green, bluish green, violet-blue, white, colorless; occasionally yellow, gray, red, flesh-red, brown. In thin section usually colorless, sometimes gray, blue, or brown. The color not uniformly distributed, but appearing as though localized in particles like inclusions, in clouds or in lines parallel to the *c* axis of the crystal. Such colored apatites exhibit weak pleochroism or absorption. $E > O$. Luster vitreous to subresinous.

Inclusions.—In some occurrences apatite is filled with minute inclusions, which appear dark in transmitted light. They are in some cases evenly distributed through the crystal; in others arranged centrally or zonally, less often marginally; sometimes in lines parallel to the *c* axis. They are in some instances gas and fluid inclusions, in others of an indeterminable character.

Occurrence.—Apatite is widespread in all kinds of rocks. It occurs most abundantly in association with metamorphosed limestones, in regions of crystalline schists, as in numerous localities in Canada, especially in Ottawa County, Quebec, and Renfrew County, Ontario, where it is accompanied by pyroxene, amphibole, titanite, zircon, garnet, vesuvianite, etc. It occurs in gneisses and schists; in the Odenwald near Schriesheim an apatite-schist occurs with 55 per cent. of apatite, 43 quartz, 2 graphite, as described by Osann. It is found in sedimentary rocks of various kinds, both as the result of organic deposits and as fragments from other rocks. It sometimes forms veins traversing granite, as on Long Island, Blue Hill Bay, Me. It is present in igneous rocks of all varieties of composition and texture; usually in microscopic crystals and in small amount. It is more abundant generally in the less feldspathic, highly ferromagnesian rocks, occasionally attaining a considerable percentage of the whole, as in the pyroxene-apatite-syenite of Ahvenvaara, Kuuo Samo, Finland.

It is commonly one of the first minerals to separate from the magma, and consequently is frequently inclosed in other crystals, especially magnetite, mica, and other ferromagnesian minerals. But it is sometimes relatively late in crystallizing, and is then inclosed chiefly in the feldspathic minerals or in quartz. In the igneous rocks it varies greatly in size and habit according to the texture and composition of the rock. In some lavas and porphyries it occurs in many minute, short, prismatic euhedrons, or in rounded anhedrons; in others in long, slender needles or hair-like crystals. In some andesites and trachytes it occurs in comparatively large, stout prisms, often colored brown or bluish, with abundant inclusions. In phanero-

crystalline rocks, granites, diorites, and gabbros, apatite is in irregularly shaped, colorless anhedrons.

Resemblances.—Apatite when euhedral is well characterized by hexagonal cross-sections, moderately high refraction, and low double refraction. It is distinguished from nephelite and quartz by higher refraction, and from quartz by lower double refraction and negative optical character. When anhedral it resembles somewhat tourmaline when not highly colored, but is distinguished by lower double refraction, and when pleochroic by the direction of greatest absorption. Anhedral apatite is similar to eudialyte and eucolite in refraction and double refraction, but is distinguished by somewhat higher refraction, by less definite cleavage, and by the chemical reactions. From anhedral melilite and gehlenite it is distinguished by its interference color and chemical reaction; and from anhedral vesuvianite by somewhat lower refraction and by the chemical reactions.

Laboratory Production.—Apatite has been obtained by Daubrée by the action of chloride-of-phosphorus vapor on lime. It has also been produced by the fusion of tribasic sodium phosphate with an excess of calcium fluoride or calcium chloride, or of both together (Manross, Briegleb). It has been obtained by passing hydrochloric acid vapor over tribasic calcium phosphate heated to red heat (Debray); and in other ways, but not yet in molten silicate solutions.

LAZULITE.

$(AlOH)_2(Mg,Fe)(PO_4)_2$.

Composition.—$(Mg,Fe)O \cdot Al_2O_3 \cdot P_2O_5 \cdot H_2O$ with $Fe:Mg(Ca) = 1:12$, $1:6$, $1:2$, $2:3$. For $1:2$, P_2O_5 45.4, Al_2O_3 32.6, FeO 7.7, MgO 8.5, H_2O 5.8 = 100, which corresponds closely to the analysis of lazulite from Sinclair County, N. C., and from Westano, Sweden. Unacted on by acids.

Monoclinic; prismatic class. $a:b:c = 0.97496:1:1.6483$, $\beta = 89°\ 13\frac{2}{3}'$. Euhedral crystals commonly acute pyramidal in habit with $p(111)$, $e(\bar{1}11)$, and $t(101)$ (Fig. 1); sometimes tabular parallel to one pair of prismatic planes (Fig. 2); also prismatic by the development of one of the prisms (111) or (111). Anhedral crystals massive or granular.

Twinning.—(1) Twinning plane (100), composition plane irregular or approximately (001); (2) rarely twinning plane (223).

Cleavage prismatic, parallel to $(\bar{1}11)$ indistinct. Fracture uneven. H. = 5–6. Sp. gr. = 3.057–3.122.

Optical Properties.—Optically negative (−); axial plane parallel to (010); acute bisectrix X inclined 9° 20′−9° 45′ to c axis, in the

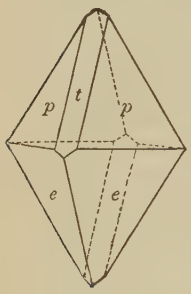


Fig. 1.

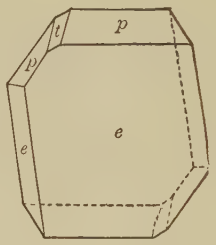


Fig. 2.

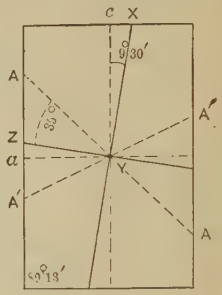


Fig. 3.

acute angle β. Dispersion in air distinct, $\rho < v$; inclined dispersion of the bisectrices. Axial angle large.

	$2E_r = 132°\ 29'$ $2E_b = 134°\ 25'$	Des Cloizeaux.
	$2E_r = 136°\ 25'$ $2E_b = 138°\ 4'$	
Graves Mt., Ga.	$2E_r = 111°$	von Lasaulx.

Refraction low, double refraction high.

Brazil, $\alpha = 1.603$, $\beta = 1.632$, $\gamma = 1.639$, $\gamma - \alpha = 0.036$, Lévy-Lacroix

Color azure-blue to bluish white. Pleochroism distinct: X colorless, $Y = Z$ azure-blue.

Occurrence.—Lazulite occurs in sandstones or quartzite of various ages in separate crystals or in veins, also in clay slate, as near Werfen in Salzburg. It occurs in veins or pockets in quartzite in Horrsjöberg, Sweden. It is abundant with corundum at Crowder's Mt., Gaston Co., N. C.; and with cyanite, rutile, pyrophyllite, etc., on Graves Mt., Lincoln Co., Ga., and elsewhere.

MONAZITE.

$(Ce,La,Di)PO_4$.

Phosphate of the cerium metals. Analyses show the presence of ThO_2 and SiO_2, which are probably due to inclosed crystals of thorite.

Alexander County, N. C., P_2O_5 29.32, Ce_2O_3 37.26, $(La,Di)_2O_3$ 31.60, SiO_2 0.32, ThO_2 1.48, ign. 0.17 = 100.15. Sp. gr. = 5.203 (Penfield and Sperry).

Difficultly soluble in hydrochloric acid.

Monoclinic; $a:b:c = 0.96933:1:0.92558$, $\beta = 76°\ 20'\ 10''$. Euhedral crystals commonly small, flattened parallel to (100) or elongated

parallel to the b axis, sometimes prismatic with the development of $v(\bar{1}11)$. Forms present $a(100)$, $b(010)$, $m(110)$, $y(310)$, $l(210)$, $n(120)$, $x(\bar{1}01)$, $w(101)$, $h(305)$, $e(011)$, $u(021)$, $r(111)$, $v(\bar{1}11)$, and others (Figs. 1, 2, 3); also in irregularly shaped anhedrons and rounded grains.

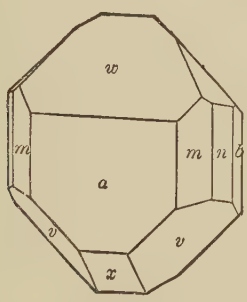


Fig. 1.

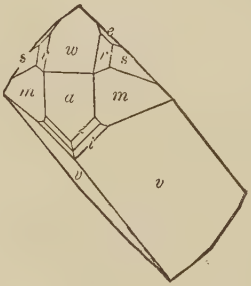


Fig. 2.

Twinning plane (100); in part cruciform twins.

Cleavage parallel to (001) sometimes perfect; parallel to (100) distinct; parallel to (010) difficult, rarely parallel to $(\bar{1}11)$. Fracture conchoidal to uneven. H. = 5–5.5. Sp. gr. = 4.9–5.3; mostly 5.0–5.2.

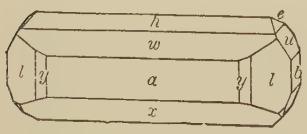


Fig. 3.

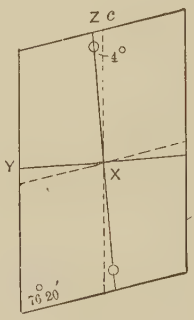


Fig. 4.

Optical Properties.—Optically positive (+); plane of the optic axes perpendicular to (010) and nearly parallel to (100) (Fig. 4). The acute bisectrix Z inclined to c axis from 2° to 6° 30′ in obtuse angle β (Pohl); 3° 1′ in acute angle β in monazite from Prägraten. Angle between the optic axes small, dispersion weak and horizontal, $\rho < v$.

Lokansaari	$2E = 22° 25'$	$Z \wedge c = -4°$	Ramsay-Zilliacus
Arendal	$2E = 23° 2'$	$= -3°$	Wülfing
New York City	$2E_y = 24° 7.5'$	$= -2°$	Bowman
Alexander Co. N. C.	$2E_y = 28° 56'$	$= -2° 15'$	Bowman
Norwich	$2E_r = 29° 4'$	$= -3° 46'$	Des Cloizeaux
Val Nalps Tavetsch	$2E_n = 36° 12'$	$= -4° 24'$	Bowman

Refraction and double refraction high.

Arendal	$\alpha=1.7957$	$\beta=1.7965$	$\gamma=1.8411$	$\gamma-\alpha=0.0454$	Wülfing
Lokansaari	$=1.7863$	$=1.7879$	$=1.8373$	$=0.0510$	Ramsay-Zilliacus
Alexander Co., N. C.	$=1.792_y$				Bowman
Val Nalps	$=1.798_y$				"

Color.—Hyacinth-red, clove-brown, reddish or yellowish brown. In thin section colorless to yellowish. Pleochroic in thick plates; on turnerite X light yellow, Y dark yellow, Z greenish yellow. Absorption distinct, $Y>Z=X$.

Occurrence.—Monazite occurs in granites and granitic gneisses, usually in minute crystals, but reaching considerable size in pegmatite. It is found in granite in the Ilmen Mountains near Zlatoust; in pegmatite near Moss and in various other localities in Norway and elsewhere in Europe; in numerous localities in the United States, especially at Amelia Court House, Va., and in Alexander, Madison, Mitchell, and Yancey counties, N. C., and elsewhere. It is wide-spread in granites and gneiss in Brazil.

Resemblances.—Monazite is distinctively characterized by its refraction and double refraction when compared with minerals with which it may be associated.

XENOTIME.

YPO_4.

Or $Y_2O_3 \cdot P_2O_5 = P_2O_5$ 38.6, Y_2O_3 61.4 = 100. The yttrium metals may include erbium in large amount; cerium is sometimes present; also silicon and thorium as in monazite; small amounts of other elements appear in the analyses. Insoluble in acids.

Tetragonal; $c=0.61867$. Euhedral crystals short prisms with the same habit as zircon: (110), (100), (111), (101), and others. Twinning plane (101).

Cleavage parallel to (110) perfect. Fracture uneven and splintery. H. = 4–5. Sp. gr. = 4.45–4.56.

Optical Properties.—Optically positive (+). Refraction and double refraction high as in zircon.

Color.—Yellowish brown, reddish brown, hair-brown, flesh-red, grayish white, wine-yellow, pale yellow In thin section colorless, yellowish, light brownish. Streak pale brown, yellowish, or reddish. Luster resinous to vitreous.

Occurrence.—Xenotime occurs in some granites and syenites and in their pegmatite veins, also to some extent in gneiss. It has been found in a granite vein at Hitterö, and in the syenite-pegmatites in the Langesund region, Norway; in localities in Sweden, Switzerland, Bohemia, and elsewhere in Europe. It occurs in considerable quantity in the muscovite granites of Brazil, and in the sands derived from such rocks in Georgia and North Carolina, and near Pike's Peak, Colo. It is often associated with zircon, with which it is sometimes grown in parallel orientation.

Resemblances.—Xenotime is most like zircon, differing from it chiefly in hardness and chemical composition. It is distinguished from cassiterite by lower double refraction; from anatase by the optical character (+). It is somewhat like titanite and monazite in refraction and double refraction, but differs from them by being uniaxial.

HUSSAKITE.

$3R_2O_3 \cdot SO_3 \cdot 3P_2O_5$.

Phosphate of yttrium (Y_2O_3 43.4), erbium (Er_2O_3 14.8), and gadolinium (?) (Gd_2O_3 2.0) with sulphur. In composition closely related to xenotime, of which it may be a variety.

Tetragonal; $c = 0.6208$. Euhedral crystals short prisms with (110), (111), (331), rarely (100); also in rounded, rolled grains.

Cleavage parallel to (110) distinct. Fracture uneven. H. = 5. Sp. gr. = 4.587.

Optical Properties.—Optically positive (+). Refraction strong, double refraction very strong. $\varepsilon_y - \omega_y = 0.0948$.

$\omega_r = 1.7166$, $\omega_y = 1.7207$, $\omega_{gr} = 1.7244$
$\varepsilon_r = 1.8113$, $\varepsilon_y = 1.8155$, $\varepsilon_{gr} = 1.8196$ } Kraus and Reitinger

Color.—Yellowish white, honey-yellow, brown to dark brown. In thin section colorless, yellowish to light brownish. Luster vitreous. In some cases weak pleochroism; *O* pale rose or light yellow-brown, *E* brownish yellow or gray-brown (Rösler).

Occurrence.—Hussakite occurs in sand from Dattas in Minas Geraes, also in clay and argillaceous sandstone and in several granitic rocks.

Resemblances.—Hussakite is possibly a variety of xenotime containing SO_3. It is like cassiterite in double refraction, but has lower refraction. It has higher double refraction than zircon, as well as lower refraction.

QUARTZ.

SiO_2.

TRIGONAL, TRAPEZOHEDRAL. $c = 1.09997$.

Twinning: not recognizable in thin section.

Cleavage: $(10\bar{1}1)$, $(01\bar{1}1)$, difficult and rarely observed, also $(10\bar{1}0)$ and sometimes (0001) almost never observed. Lamellar structure due to gliding planes $\parallel (10\bar{1}1)$ and $\parallel (01\bar{1}1)$ developed by secondary means according to Judd.

Fracture: conchoidal. Brittle to tough. H. = 7. Sp. gr. = 2.660, Penfield.

OPTICAL PROPERTIES: Uniaxial. Rotary polarization, not observable in thin section. Optically positive (+). $v_o > v_e$. $\epsilon_D = 1.55328$, $\omega_D = 1.54418$. $\epsilon - \omega = .0091$.

Color: colorless in thin section. In thicker crystals colorless, gray, yellow, brown to black, amethystine, blue, green, red, white. *Luster:* vitreous.

Chemical Composition.—SiO_2, silicon dioxide, composition invariable. Inclusions of other substances, gaseous, liquid, or solid, affect the analysis of a quartz crystal, but the mineral itself has a fixed, definite composition. Unattacked by acids other than hydrofluoric, slightly attacked by solutions of fixed caustic alkalies. This resistance to the attack of ordinary acids explains the general absence of alteration in the quartz crystals of rocks, except where they have been subjected to profound metamorphism. Ordinary processes of alteration and decomposition do not affect quartz. They appear fresh and unaltered when other minerals have been decomposed. Evidences of modification in quartz are in most instances mechanical.

Crystal Habit.—*Euhedral.*—When rock-making quartz possesses its own form it is bounded by plus and minus rhombohedrons $r(10\bar{1}1)$, $z(0\bar{1}11)$, nearly equally developed, and therefore resembling a hexagonal bipyramid. In some cases the prism $m(10\bar{1}0)$ is present as a subordinate form (Figs. 1 and 2). When the crystals project into cavities the habit is more prismatic and the terminal faces more highly modified.

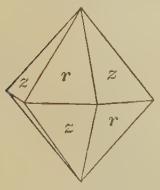


FIG. 1.

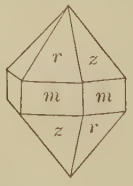


FIG. 2.

The habit of euhedral quartzes in igneous rocks is the same whether they are phenocrysts in porphyries

or microscopic crystals in rock glasses, obsidian. That is, microlitic quartzes have the same habit as megascopic ones.

Cross-sections of euhedral quartzes are six-sided; longitudinal sections are rhombic, with acute angles ranging from 76° 26′ to nearly 90°, according to the position of the section. When subordinate prism faces occur the longitudinal sections also are six-sided.

Euhedral quartzes occur mostly as phenocrysts in porphyries, and to some extent in porphyritic granites. They occur less often as components of non-porphyritic granite and of the groundmass of certain finer-grained rocks. Clusters of two or more subhedral quartzes occur in igneous rocks, but they are not so common as separate euhedral crystals.

Subhedral.—Quartzes that are partly bounded by crystal faces and partly irregular are of four categories: (1) Those grown free in certain directions and against other crystals in other directions, such as a cluster of quartz phenocrysts, less often a cluster of quartz and feldspar phenocrysts. (2) Those quartzes grown simultaneously with feldspar, occasionally with other minerals, in graphic intergrowth. In this case the quartzes are to some extent bounded by prismatic faces and by inclined faces, possibly trapezohedrons, and to a large extent they are bounded by irregularly shaped surfaces, often rounded. (3) Those quartzes which are more or less rounded on the edges and angles but still retain their characteristic shapes. This category embraces crystals that were at one time euhedral and have been rounded by solution in the liquid magma, and crystals that grew in the first instance with more or less rounded shapes. The former are represented, no doubt, by many rounded phenocrysts in porphyries, certainly by those quartz phenocrysts in basic rocks that are plainly surrounded by glass as the result of magmatic solution. Examples of quartzes that have crystallized in rounded forms are found in some gneisses, the rounded quartzes being inclosed in feldspars. (4) There are in some porphyries quartz phenocrysts that crystallized in hedral forms but have cracked into irregularly shaped fragments and have been spread apart in the liquid magma. Such fragments may be more or less hedral.

Anhedral.—In the great majority of cases rock-making quartzes are anhedral, having crystallized against one another or other minerals. Their cross-sections are irregular in outline, in no way characteristic of the crystal. They may have an irregularly straight-edged or somewhat curved outline, which may be called *uneven.* Or the outline may be distinctly *rounded,* or quite jagged or *serrated.*

Uneven anhedral quartzes are common in nearly all holocrystalline quartz-bearing rocks, such as granite and many quartzites. Serrated anhedral quartzes occur in a great number of metamorphic rocks, gneisses, schists, and some quartzites. Rounded anhedral quartzes occur as phenocrysts in some porphyries, as portions of graphic quartz in feldspar or other minerals, and as separate inclusions in other minerals in many metamorphic rocks.

Twinning frequently occurs in rock-making quartzes, but is not recognizable in thin sections. It may be determined in thick sections by the optical behavior of the interference figure. It may also be observed when the quartzes are immersed in liquids having the same index of refraction (Klein's method), and it may be recognized by means of etching in hydrofluoric acid.

Cleavage.—In most cases cleavage is not developed in quartzes in rocks, which generally serves to distinguish them from feldspar. In rare instances imperfect cleavage parallel to the rhombohedral faces is present. Other possible cleavages have not yet been noted in rock-making quartzes.

Fracture.—The conchoidal fracture of quartz shows itself in more or less curved cracks, which in some occurrences approach spheroidal or perlitic forms.

Optical Properties.—Colorless in thin section, quartz is perfectly transparent, with nearly the same refraction as that of Canada balsam. It appears to have a very smooth surface and a faint outline, often difficult to recognize. It does not stand out in relief in comparison with other minerals or with balsam. Its refraction is slightly higher than that of balsam. $\epsilon_D = 1.55328$, $\omega_D = 1.54418$, for yellow light. The ordinary ray is faster than the extraordinary. Optically (+). The index of refraction of the faster ray in all sections is constant = 1.54418, and may be used as a basis for comparison.

The double refraction is low, 0.0091. All sections less than 0.04 mm. thick show gray of the first order as the interference color. In rather thick sections, 0.05 to 0.06 mm., the color reaches red of the first order. A uniaxial interference figure is obtainable from cross-sections which exhibit little or no double refraction, and the character of the double refraction is readily determined.

In some cases the interference cross separates slightly into hyperbolas indicating molecular strain within the quartz. This is also shown in other cases by the variation in the interference color in the section of a quartz crystal. The color or shade of darkness undulates over the section when it is turned slightly; the directions of

vibration of light are not the same in all parts of the crystal. There is molecular distortion, usually the result of stresses undergone by the rock mass. Occasionally such molecular distortion is found about inclusions within a quartz crystal, indicating a difference in the contraction of the two substances upon cooling after crystallization.

Color.—In a perfectly pure state quartz is transparent and colorless, and in thin section quartz substance is colorless. The various colors exhibited by quartz crystals megascopically arise from pigment often so dilute as to escape recognition with a microscope, as in smoky quartz. In other cases the coloring-matter is visible microscopically. Milky-white color is generally due to the reflection of light from inclusions of gas or liquid. Sky-blue color is due in some cases to the reflection of light from mineral inclusions thinner than half a wave length of light. In other cases blue color is due to magnetite. Green colors often arise from inclusions of green minerals, such as chlorite or actinolite; yellow, orange, and red colors, from inclusions of iron oxides.

It is to be noted that quartz is usually among the light-colored constituents of rocks, but may often be the darkest mineral visible megascopically, as in some varieties of rapakiwi from Finland, and in the rhyolite of Eureka, Nevada.

Inclusions.—Certain kinds of inclusions occur so frequently in quartz as to be characteristic of particular modes of occurrence of the quartz.

Gas and *fluid* inclusions in irregularly shaped cavities are most common in anhedral quartzes in all kinds of rocks. The relative proportions between gas and liquid vary widely within one quartz crystal. Where the gas bubble is relatively small it is usually in motion. The liquid is in most cases water, but liquid carbon dioxide is not uncommon, the most notable occurrence being that in the quartz of a coarse pegmatite at Branchville, Conn. The nature of the gas is not generally known, except that it must be in part water vapor. In the smoky quartz at Branchville it has been determined by A. A. Wright to be CO_2, N, H_2S, SO_2, H_3N, and F.

There are in some fluid inclusions colorless cubical crystals whose composition has not been determined. The distribution of fluid inclusions is in some quartzes quite indefinite; in others it is in planes or lines through the crystal, as though along former cracks. In this case the secondary nature of the inclusions is indicated, a crack having been filled up with quartz except in the spaces occupied

by liquid and gas. In igneous rocks the size of primary fluid inclusions sometimes bears a general relation to the size of the quartzes in one rock mass, being larger in the larger quartzes than in the smaller ones. The shape of the cavity is less often that of a quartz crystal, the cavity being bounded by crystal planes.

Glass and *groundmass* inclusions occur in euhedral and rounded quartzes, which are usually phenocrysts in porphyries. The shape of the inclusions is generally rounded or corresponds to the form of the quartz crystal, the plus and minus rhombohedrons. All those in one quartz have like orientation. Occasionally there are minute fractures parallel to the axial planes (Fig. 37, p. 71). The glass inclusion may contain a gas bubble, besides microscopic crystals. The character of the glass inclosed in the quartz may be like that of glass surrounding the quartz or it may be different. Glass may exist within quartz phenocrysts when the groundmass of the rock is holocrystalline. In some cases the inclusion is holocrystalline, like the groundmass surrounding the quartz. It seldom happens that glass or groundmass inclusions are very abundant in one quartz crystal, as they sometimes are in feldspars.

Mineral inclusions may be of any kind that occurs in the rock, since quartz not infrequently is the last constituent to crystallize; but certain kinds of minerals are more frequently met with than others, and some are specially located in the quartzes. This is the case with extremely thin microscopic needles having high refraction, which are rutile. They may be very abundant. They characterize the quartz of some granites, gneisses, etc. Minute crystals of apatite and plates of ilmenite abound in blue quartzes in certain porphyries and granites. In a very large majority of cases quartz is free from characteristic mineral inclusions.

Poikilitic quartz, containing abundant crystals of feldspar or other minerals, occurs as a primary crystallization in igneous rocks, both phanerocrystalline and microcrystalline. The quartz was the last constituent to crystallize and formed a matrix for other constituents. In some porphyries it produces a micropoikilitic groundmass. Poikilitic quartz also occurs in metamorphosed rocks, both phaneritic and aphanitic. It has been developed in the groundmass of certain porphyries, as in aporhyolite of South Mountain, Pa.

Graphic quartz is most frequently developed with alkali feldspar, oftener potash-feldspar, orthoclase, or microcline; less often with albite or oligoclase, and rarely with garnet or tourmaline. It occurs in coarse-grained pegmatites, in granite of various grain, and in

aphanitic rocks, mostly as components of the groundmass, but in some cases as phenocrysts, megascopic or microscopic. It is probably graphic quartz that occurs in spherulites when quartz is present in these forms of crystallization. Graphic quartz does not occur in metamorphic rocks, though poikilitic quartz is common. It is probably wholly a product of primary crystallization from a rock magma, and not a deposit from secondary aqueous solutions.

Modes of Occurrence.—Quartz is a primary constituent of igneous rocks, having crystallized directly from the molten magma. It occurs as phenocrysts in holocrystalline as well as in glassy porphyries, and as microlites in some obsidians. It forms a primary constituent of the groundmass of many igneous rocks, in some cases of rocks quite low in silica, its presence depending on the relative proportions of the chemical elements and on the minerals crystallized.

Quartz occurs in metamorphic rocks, both as an unaltered constituent of the original rock in some instances, and as a product of recrystallization through metamorphic agencies. It occurs as a crystallization from aqueous solutions, hot or cold, deposited in fissures or other cavities, or disseminated through a mineral mass as a more or less complete replacement of a former mineral. Finally, it occurs in fragmental rocks as fragments of any of the kinds of quartz just mentioned.

Laboratory Production.—Quartz has been obtained in the laboratory by heating hydrous silica in closed tubes at a moderate temperature, and by heating water in a closed glass tube. It has been crystallized from a mixture of silica and sodium or lithium tungstate fused at a temperature of about 900° C. But only recently has it been obtained from a fused silicate solution in an open crucible.

CHALCEDONY.

SiO_2.

Chemical Composition.—SiO_2, like quartz.

Crystal Habit.—Chalcedony occurs in aggregates of radiating, and also of parallel, fibers, the shape of whose cross-section is irregular. These spherulitic aggregations have crystallized from walls of fissures or cavities like agate. There are no indications as to the system of crystallization. H. = 7. Sp. gr. = 2.59–2.64.

Optical Properties.—Chalcedony is colorless in thin section, has about the double refraction of quartz, but a little lower, and has a noticeably lower index of refraction, $n_\rho = 1.537$, almost identical

with that of Canada balsam, slightly lower. The fibers of chalcedony have parallel extinction. The ray vibrating parallel to the length of the fiber is the fastest. If the fibers were quartz elongated parallel to the *c* axis, this ray would be the slowest.

Color.—Pale colors of various tones to black, translucent to transparent. In thin section colorless. Luster wax-like.

Modes of Occurrence.—Chalcedony is a secondary mineral deposited in cavities as a result of infiltration or alteration of silicate rocks. It may occur in any kind of siliceous rock, igneous, metamorphic, or sedimentary.

There are several other forms of silica that have been observed, but they are of such rare occurrence that a detailed description is not necessary in this place.

Lussatite is a fibrous scaly aggregate with weaker double refraction than that of quartz. The ray vibrating parallel to the length of the fiber is the slowest. $n_{na}=1.446$. Sp. gr. $=2.04$. (E. Mallard, Bull. Soc. Min. Fr., 1890, XIII, 62.)

Quartzin and *lutecite* are less definitely determined varieties described by Michel-Lévy and Munier-Chalmas. (Comptes Rendus 24 Mars, 1890.)

TRIDYMITE.

SiO_2.

Chemical Composition.—SiO_2. Silicon dioxide, like quartz. Soluble in boiling sodium carbonate.

Hexagonal at 130° (Mallard). $c=1.65304$.

Crystal Habit.—Euhedral crystals are thin hexagonal plates bounded by $c(0001)$, $m(10\bar{1}0)$, with subordinate $a(11\bar{2}0)$, $p(10\bar{1}1)$ (Fig. 1). Often twinned parallel to $(10\bar{1}6)$ or $(30\bar{3}4)$ in wedge-shaped juxtaposition twins or trillings (Figs. 2 and 3); often penetration forms, fan-shaped groups, and spherical aggregations. These are the habits of crystals grown in cavities. They are usually very small, 5 mm. and less in diameter. In still smaller aggregates in rocks they appear as hexagonal and less regular plates, and sometimes resemble the tiling on a roof. Anhedral forms of microscopic proportions are not specially noteworthy.

Cleavage parallel to $(10\bar{1}0)$ indistinct; sometimes a parting parallel to (0001). Fracture conchoidal. H. $=7$. Sp. gr. $=2.28$–2.33.

Optical Properties.—Colorless in thin sections. Although uniaxial at moderately high temperatures, it appears to be biaxial at ordinary

temperatures, and has been considered by von Lasaulx to be triclinic. Optically positive (+). The average index of refraction is 1.4775 (Mallard), with $\gamma-\alpha=.00185$, $\gamma-\beta=.00025$, $\beta-\alpha=0.0016$. $2E=66°$ approximately, corresponding to $2V=43°$. In thin section the double refraction is so weak as to be scarcely perceptible in some cases. In other cases various parts of one crystal exhibit different

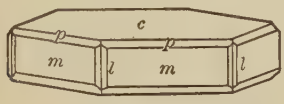


FIG. 1.

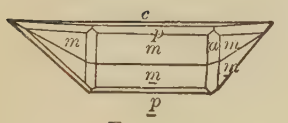


FIG. 2.

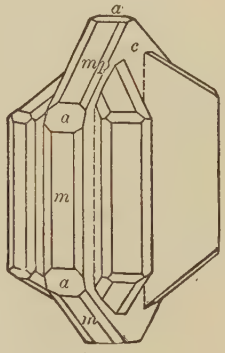


FIG. 3.

optical orientation, as though the crystal were twinned in more than one position.

Color.—Colorless to white. In thin section colorless. Luster vitreous; pearly on basal pinacoid.

Inclusions.—Gas inclusions are the only kind that occur with any frequency. Otherwise tridymite is quite free from inclusions.

Modes of Occurrence.—Tridymite occurs frequently in volcanic lavas, especially the more siliceous and feldspathic kinds. It occurs in small aggregations in the massive rock, and often in cavities associated with quartz and feldspar. It is sometimes associated with amorphous silica, opal, and cacholong in these rocks. It has been found in meteorites. It does not occur in the phanerocrystalline rocks.

Laboratory Production.—Tridymite has been produced by heating gelatinous silica with an alkaline solution in a closed tube at a red heat. Quartz has been formed in the same vessel at a lower temperature. Tridymite is formed when a silicate is decomposed in a salt of phosphorous bead with the separation of a skeleton of silica. It has been formed in the walls of the muffles of a zinc furnace.

OPAL.

$SiO_2 + nH_2O$.

Composition.—*Silica* with variable amounts of water, from 2 to more than 13 per cent., mostly from 3 to 9 per cent. A hyalite gave 3 per cent.; fire-opal 6–8 per cent.; precious opal from Hungary 10 per cent.; geyserite 9–13 per cent. Quartz is often present in some instances, in others tridymite. Soluble in hydrofluoric acid somewhat more readily than quartz, and soluble in caustic alkalies, more readily in some varieties than in others.

Amorphous. In irregularly shaped masses filling cavities or replacing other minerals, as pseudomorphs, after feldspar, pyroxene, etc. Sometimes on the walls of cavities, when it is reniform or stalactitic. Also earthy. Fracture conchoidal, cracks frequent. H. = 5.5–6.5. Sp. gr. = 1.9–2.3; when pure 2.1–2.2.

Optical Properties.—Isotropic, often exhibiting double refraction due to strained condition. Mammillary forms, hyalite, often show uniaxial interference figures of a negative character, indicating a shrinkage and radial compression. The index of refraction is low, considerably below that of balsam.

Colorless precious opal, Guatemala	$n_r = 1.446$	Des Cloizeaux
" not iridescent "	$= 1.442$	"
Deep yellow (fire-opal) "	$= 1.450$	"
Hyalite	$= 1.4374$	"
"	$= 1.4555$	"
" Waltsch, Bohemia	$n_y = 1.458$	Zimanyi
Hydrophane, Czerwenitza, dry	$n = 1.368$	E. Reusch
" " saturated with water	$= 1.443$	"
" " " " alcohol	$= 1.451$	"

Color.—White, yellow, red, brown, green, gray, blue, generally pale; dark colors due to impurities. Sometimes exhibiting bright iridescent interference colors. In thin section colorless. The interference colors appear to be due to the presence of lamellæ of opal having different indices of refraction, possibly differently hydrated (Behrens).

Modes of Occurrence.—Opal is a common alteration product in igneous rocks, and also occurs like flint in limestone, and like quartz concretions in argillaceous beds. It is deposited from the waters of hot springs and geysers. In igneous rocks it occurs filling cavities or veins, and as pseudomorphs after various altered minerals.

Precious opal occurs in porphyry at Czerwenitza, Hungary, and at Frankfort; in rhyolite at Esperanza, Mexico, with fire-opal, milk-opal, and other kinds. A blue precious opal occurs on Bulla Creek, Queensland, and in New South Wales, Australia. *Fire-opal* occurs at Zimapan, Mexico. *Common opal* occurs in all parts of the world and in all kinds of lavas. *Wood-opal*, replacing buried trees in volcanic tuffs, is common in regions of extinct volcanoes and of hot springs. It is associated with chalcedony, agate, and quartz. *Siliceous sinter*, including fiorite and geyserite, is deposited by hot springs after the decomposition of igneous rocks. It is usually more or less porous, fibrous, or filamentous, but may be compact and massive.

Many names have been given to amorphous silica or opal in different modifications, a few of which have been mentioned. *Hydrophane* is a translucent whitish or light-colored variety that absorbs water rapidly, becoming more translucent or transparent in water. For other varieties see Dana's System of Mineralogy.

Resemblances.—In thin section opal may be mistaken for Canada balsam or for isotropic leucite or sodalite, but it is recognized by its lower refraction and its appearance in diaphragmed light, and by its usual occurrence as incrustations in amygdaloidal cavities or veins.

Laboratory Production.—Opal has been formed by the gradual drying of gelatinous silica.

BROOKITE.

TiO_2.

Titanium dioxide, the same as octahedrite and rutile. Insoluble in acids. Sometimes alters to rutile.

Orthorhombic; $a:b:c=0.84158:1:0.94439$.

Euhedral crystals often tabular parallel to $a(100)$ (Fig. 1), with $m(110)$, sometimes $b(010)$, and bipyramidal planes $e(122)$, $z(112)$, and others. Planes in zone (100)(010) often striated parallel to the vertical axis c. Sometimes the crystal habit is prismatic with $m(110)$ dominant, resembling rutile. Anhedral crystals rare.

Cleavage parallel to (110) indistinct, seldom observed in microscopic crystals. Fracture subconchoidal to uneven. H.=5.5–6. Sp. gr.=3.87–4.084.

Optical Properties.—The acute bisectrix Z is parallel to crystal axis a. Optically positive (+). But the plane of the optic axes

is parallel to (001) for red and yellow light, and parallel to (010) for green and blue. The mineral is therefore uniaxial for an intermediate yellow-green ray. The resulting interference figure in white light is anomalous, being composed of sets of highly dispersed biaxial figures at right angles to one another. Axial dispersion strong; in the plane parallel to (001), $\rho > v$. Upon heating, the optic axes parallel to (010) approach one another, and separate in the plane (001)

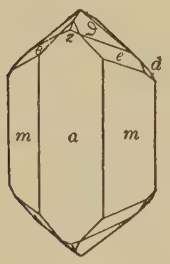


Fig. 1.

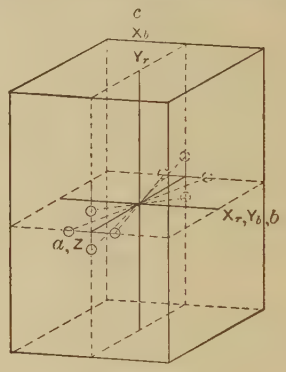


Fig. 2.

after passing parallelism. The change is temporary unless a temperature of low red heat is reached, when it remains fixed, Des Cloizeaux. Axial angle variable for different localities. $2E_r = 55° 2'$, $2E_y = 30° 16'$, $2E_{y-gr} = 0°$, $2E_{gr} = 33° 48'$, Zepharovich and Lippich.

The refraction and double refraction are very high.

$\alpha_r = 2.5408$, $\beta_r = 2.5418$, $\gamma_r = 2.6444$ (Tremadoc), Wülfing.
$\alpha_y = 2.5832$, $\beta_y = 2.5856$, $\gamma_y = 2.7414$.
$\alpha_{gr} = 2.6265$.

$$\gamma_y - \alpha_y = 0.1582,\ 2V_r = 23° 14',\ 2V_y = 17° 7'.$$

Color.—Brown, yellowish, reddish, translucent; also brown to iron-black, opaque. In thin section yellowish, reddish, brownish to colorless, rarely bluish to greenish blue. Luster metallic-adamantine to submetallic.

Modes of Occurrence.—Brookite is found in mica in such a manner as to appear to be of secondary origin, accompanying the alteration of this mineral. In such connection it occurs in some granite and porphyry, in gneiss and crystalline limestone. It is often accompanied by anatase or rutile. At Magnet Cove, Ark., it occurs with nephelite, black garnet, schorlomite, rutile, etc. At this locality

it is sometimes altered to rutile. It occurs as a pseudomorph after titanite in crystalline limestone at St. Philippe in the Vosges.

Resemblances.—Brookite is like rutile and cassiterite in its high index of refraction, but is distinguished by its tabular form in most cases, and when in prismatic crystals by the variable double refraction exhibited by its prisms according as the light vibrates parallel to X and Z, 0.1582, or to X and Y, 0.0024.

Laboratory Production.—Brookite has been obtained by Daubrée and Hautefeuille by passing steam and titanium chloride vapor through a heated tube, or by passing titanium chloride over lime. Brookite, anatase, and rutile may be formed by the same process, but at different temperatures, brookite requiring a lower temperature than rutile.

ANATASE (Octahedrite).

TiO_2.

Titanium dioxide, as in brookite and rutile. Insoluble in acids.

Tetragonal system; $c = 1.7771$.

Crystals commonly bipyramidal, steep, $p(111)$ (Fig. 1), or obtuse, $v(117)$ (Fig. 2); also tabular with $c(001)$, $p(111)$, and $a(100)$ (Fig. 3)

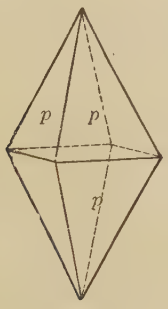


Fig. 1

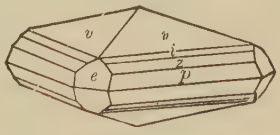


Fig. 2.

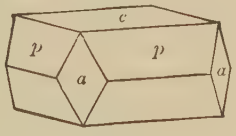


Fig. 3.

rarely prismatic. Other forms occur in combination, $m(110)$, various bipyramids and ditetragonal bipyramids.

Cleavage parallel to (001) and (111) perfect. Noticeable in thin sections when the crystals are not too small. Fracture subconchoidal. H. = 5.5–6. Sp. gr. = 3.82–3.95.

Optical Properties.—Optically negative (−). Index of refraction very high, double refraction and dispersion strong.

$\omega_r = 2.5183$, $\epsilon_r = 2.4523$ (Binnenthal), Wülfing.
$\omega_y = 2.5618$, $\epsilon_y = 2.4886$, $\omega_y - \epsilon_y = 0.0732$, "
$\omega_{gr} = 2.6066$, $\epsilon_{gr} = 2.5262$, "

In darker-colored portions sometimes biaxial with slight angle between the optic axes.

Color.—Various shades of yellow and brown, sometimes indigo-blue or black. In thin section lighter shades of the same colors, sometimes unevenly distributed or zonally. Somewhat pleochroic; in yellow crystals, *O* orange, *E* yellow; in blue crystals, *O* deep blue, *E* light blue. Luster adamantine or metallic-adamantine.

Mode of Occurrence.—Anatase occurs in small amounts in rocks of all kinds, probably as an alteration product of titaniferous minerals. It is found with partially altered mica in granite, diorite, and other igneous rocks; in gneiss, schists, quartzite, and limestones.

Laboratory Production.—It has been produced in the same manner as brookite and rutile (q.v.). It crystallizes in borax beads and those of phosphorus salt in which TiO_2 has been dissolved before the blowpipe.

RUTILE.

TiO_2.

Titanium dioxide, like brookite and anatase. A little iron is usually present, sometimes 10 per cent.; less often a little tin. Insoluble in acids. Rutile in the crystalline schists sometimes alters to a leucoxene-like mineral which is the same as titanite. This is sometimes accompanied by the formation of ilmenite.

Tetragonal system; $c = 0.644154$.

Euhedral crystals commonly prismatic, the surface striated parallel to the *c* axis. Forms in combination *m*(110), *a*(100), *l*(310),

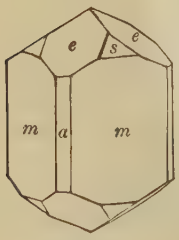


Fig. 1.

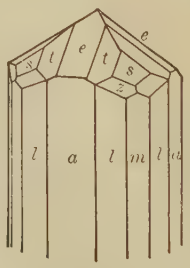


Fig. 2.

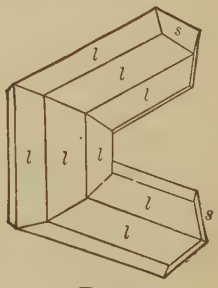


Fig. 3.

e(101), *t*(313), *z*(321), and others (Figs. 1 and 2); often very slender, acicular or hair-like when microscopic, also anhedral.

Twinning plane and composition plane (101) often geniculated (Fig. 3), sometimes in a network called *sagenite* (Fig. 4). Also contact twins of varied habit. At Magnet Cove one in which the composition plane is perpendicular to (101). A second mode of twinning is on a plane (301) rare. Rutile is sometimes twinned polysynthetically in thin lamellæ parallel to (101), which is visible in cross-section. The lamellæ are of various lengths and are irregularly distributed in the crystal, as shown in Figs. 5 and 6 (after von Lasaulx).

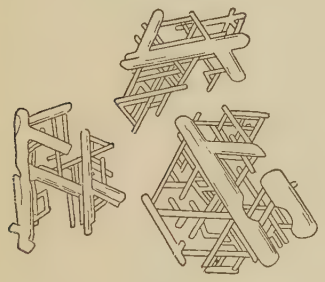


Fig. 4.

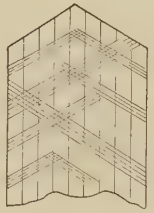


Fig. 5.

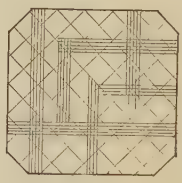


Fig. 6.

Cleavage parallel to (110) and (100) distinct; parallel to (111) in traces. Fracture subconchoidal to uneven. H. = 6–6.5. Sp. gr. = 4.18–4.25; in a black variety from the Ilmen Mountains, with 10 per cent. Fe_2O_3, sp. gr. = 5.074–5.133.

Optical Properties.—Optically positive (+). Polysynthetically twinned crystals yield abnormal interference figures. Indices of refraction and double refraction very high, so that microscopic crystals exhibit strong shadows from total reflection of transmitted light, appearing opaque often when transparent.

$\omega_r = 2.5671$, $\varepsilon_r = 2.8415$ (Syssersk, Ural), Bärwald.
$\omega_y = 2.6158$, $\varepsilon_y = 2.9029$, $\varepsilon_y - \omega_y = 0.2871$.
$\omega_{gr} = 2.6725$, $\varepsilon_{gr} = 2.9817$.

Color.—Reddish brown, passing into red; sometimes yellowish, bluish, violet, black, rarely grass-green. In transmitted light yellow, fox-red, brownish red, or violet. Variably pleochroic: in thin sections, *O* yellow to brownish, *E* brown-yellow to yellow-green; in thicker sections, *O* brownish red, *E* dark blood-red to black. Streak pale brown. Luster metallic-adamantine.

Occurrence.—Rutile is found in igneous, metamorphic, and sedimentary rocks. In igneous rock it is sometimes in hair-like

crystals penetrating quartz in granite. It is probable that this mode of occurrence is pyrogenetic. More commonly it is an alteration-product of mica, occurring in microscopic prisms often parallel to the plane of cleavage and to the directions of the rays of the percussion figure in the mica. It occurs in long needles in the andesites of Pachuca in Mexico, Assuk in Greenland, and from Pack Saddle Island, Cape Horn.

Rutile is common in gneiss, mica-schist, and phyllite, and sometimes in granular limestone and dolomite. It occurs regularly oriented in certain micas, tabular hematite, and ilmenite; rutile prisms lying in the basal plane parallel to three directions, intersecting at 60° or 120°. Rutile occurs as an alteration-product of titanite in eleolite-syenite of Serra de Monchique, and as a paramorph after brookite at Magnet Cove, Ark.

Resemblances.—Rutile is most like cassiterite and zircon, but is distinguished by its higher refraction and double refraction. It resembles anatase, brookite, and pseudobrookite in refraction and colors, but differs from them in crystal habit and cleavage.

Laboratory Production.—Rutile has been produced by a number of processes, already mentioned in connection with brookite. It has also been produced by Hautefeuille by dissolving amorphous TiO_2 in molten sodium tungstate or vanadate, in calcium chloride or in acid silicates.

BADDELEYITE.

ZrO_2.

Zirconium dioxide with a small amount of iron oxides. Insoluble in acids.

Monoclinic; $a:b:c=0.9871:1:0.5114$, $\beta=81°\ 14.5'$.

Euhedral crystals tabular parallel to (100), with (001), (110), ($\bar{1}11$), also (221), ($\bar{1}01$), and (021) subordinate.

Twinning plane (100), often polysynthetic; also parallel to (110), contact and penetration twins; also parallel to (201) rare.

Cleavage parallel to (001) rather perfect; parallel to (010) less so; parting parallel to (110) in consequence of lamellar twinning. Fracture subconchoidal and uneven. H.=6.5. Sp. gr.=6.025, Fletcher; 5.006 and 5.5+, Hussak.

Optical Properties.—Optically negative (−); plane of the optic axes parallel to (010); acute bisectrix X inclined to c axis about 13° in obtuse angle β, Fletcher, 11° 8′, Hussak, Fig. 1. $2E=70°–75°$. Refraction and double refraction high.

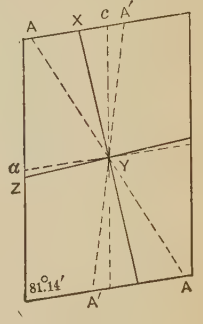


Fig. 1.

Color.—Rarely colorless; yellow, brown, to iron-black. In thin section colorless, yellow, brown; often zonally or irregularly variable. Occasionally exhibiting hour-glass structure. Pleochroic in thick plates: X reddish brown, Y oil-green, Z reddish brown. Streak white to brownish white. Luster greasy to vitreous; submetallic on opaque crystals.

Occurrence.—Baddeleyite has been found in the gem-bearing sands of Rakvana in Ceylon by Fletcher, and in the sands from jacupirangite at Jacupiranga, Brazil, by Hussak, formerly called by him brazilite. It has also been found in segregations of magnetite and olivine in nephelite-syenite at Alnö, Sweden.

CASSITERITE.

SnO_2.

Tin dioxide. A little Ta_2O_5 is sometimes present, also Fe_2O_3. Only slightly acted on by acids.

Tetragonal system; $c=0.67232$.

Euhedral crystals usually bipyramids, $s(111)$, with subordinate $e(101)$ (Fig. 1). Also short prisms, $m(110)$ and $a(100)$ (Fig. 2); rarely with $z(321)$ and $h(210)$, resembling zircon (Fig. 3). Often in irregularly shaped anhedrons; also in divergent fibrous aggregates.

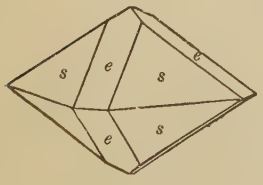


Fig. 1.

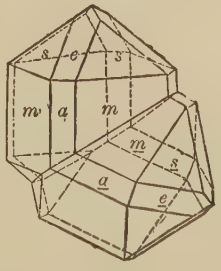


Fig. 2.

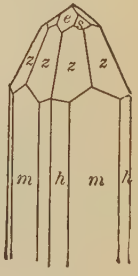


Fig. 3.

Twinning plane and composition plane (101) (Fig. 2), both contact and penetration twins. Often repeated producing complex forms.

Cleavage parallel to (100) imperfect; parallel to (111) less so; parallel to (110) hardly distinct. Fracture subconchoidal to uneven. H. = 6–7. Sp. gr. = 6.8–7.1.

Optical Properties.—Optically positive (+). Indices of refraction and double refraction high.

$\omega_r = 1.9793$, $\varepsilon_r = 2.0799$ (Schlaggenwald), Grubenmann.
$\omega_y = 1.9966$, $\varepsilon_y = 2.0934$, $\varepsilon_y - \omega_y = 0.0968$.
$\omega_{gr} = 2.0115$, $\varepsilon_{gr} = 2.1083$.
$\omega_r = 1.9765$, $\varepsilon = 2.0748$ (Zinnwald), Locke.
$\omega_y = 1.9923$, $\varepsilon_y = 2.0911$, $\varepsilon_y - \omega_y = 0.0988$.

Occasionally exhibits weak optical anomalies.

Color.—Brown or black; sometimes red, gray, white, or yellow. In thin section colorless, yellowish, brown, or reddish. Sometimes irregularly distributed in streaks or spots, less often zonal. Slightly pleochroic, not noticeable in thin section. Streak white, grayish, brownish. Luster adamantine.

Occurrence.—Cassiterite occurs sparingly in granite and pegmatite veins and especially in greissen. It is associated with tourmaline, topaz, fluorite, etc.

Resemblances.—Cassiterite is most like zircon in optical properties, but differs from it generally in crystal habit, though the two are nearly isomorphous. It is not so common as zircon. Its absolute distinction rests on chemical tests. Cassiterite is distinguished from rutile by its lower refraction and double refraction. It differs from anatase by being optically positive, and from brookite and pseudobrookite by its crystal habit and uniaxial character.

Laboratory Production.—Cassiterite has been obtained in crystals by the action of hydrochloric acid gas on SnO_2, Deville; also by the action of steam on chloride or fluoride of tin, Daubrée.

CORUNDUM.

Al_2O_3.

Chemical Composition.—Alumina, Al_2O_3. Not acted on by acids. Corundum alters into a number of different aluminous minerals: muscovite, spinel, cyanite, fibrolite, zoisite, margarite, and others.

Trigonal; scalenohedral; $c = 1.3630$.

Crystal Form.—Corundum crystals are commonly hexagonal prisms of the second order, $a(11\bar{2}0)$, and steep hexagonal bipyramids, $v(44\bar{8}3)$ (Fig. 1), often rough and rounded. They are sometimes

bounded by $c(0001)$, $r(10\bar{1}1)$, and $a(11\bar{2}0)$ (Fig. 2). They also occur as hexagonal plates. Sections are hexagonal or have long tapering or rectangular shapes. They are often in anhedral forms.

Twinning plane the unit rhombohedron $(10\bar{1}1)$; in penetration twins, often in polysynthetic lamellæ. Twinning is much commoner in corundum in the older crystalline rocks than in that of

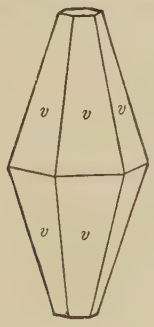


Fig. 1.

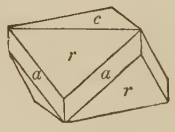


Fig. 2.

recent volcanic rocks, and it has been suggested by Mügge that it may be due to mechanical stresses.

Cleavage parallel to (0001) and parting along twinned lamellæ is often well developed in large crystals but is rarely observed in microscopic ones. Fracture uneven to conchoidal. H.=9. Sp. gr.=3.95–4.10.

Optical Properties.—Corundum is uniaxial and negative (−), but in some larger twinned crystals is biaxial. The double refraction varies irregularly within one crystal. The optical anomaly appears to be directly connected with the twinning. The index of refraction is high, and double refraction a little less than that of quartz.

Sapphire, $\omega_r = 1.7676$–1.7682, $\epsilon_r = 1.7594$–1.7598, $\omega - \epsilon = 0.0082$–$0.0084$.
Ruby, $\omega = 1.7675$, $\epsilon = 1.7592$ (Dx.), $\omega - \epsilon = 0.0083$.
Corundum,
Ceylon, $\omega_y = 1.7690$, $\epsilon_y = 1.7598$ (Osann), $\omega - \epsilon = 0.0092$.

The relief and outline of sections of corundum are about the same as those of epidote or ægirite. The interference colors are about the same as those of quartz for sections of the same thickness.

Color.—Corundum is often colorless both in thick crystals and in thin sections. When colored, the color is sometimes unevenly distributed in spots or streaks or in zones. It may be blue (sapphire), red (ruby), brown, yellow, or green. When strongly colored it is pleochroic. In blue varieties O is blue, E is sea-green, bluish to color-

less. $O > E$. Corundum is phosphorescent with a rich red color. Luster adamantine to vitreous.

Inclusions.—There are no specially characteristic inclusions in corundum. Gas and fluid inclusions are common, the fluid in some cases being liquid carbon dioxide. Glass inclusions occur in corundum in lavas. Ilmenite and rutile are frequently included in the larger crystals of corundum, but are rare in microscopic ones. In some cases rutile needles are arranged in three directions parallel to the edges $(0001)(11\bar{2}0)$, producing asterism in plates parallel to the base (0001).

Modes of Occurrence.—Corundum forms a primary constituent of igneous rocks rich in alumina, that is, feldspathic rocks, both high and low in silica. It occurs in granite, syenite, and nephelite-syenite, sometimes constituting as high as 40 per cent. of the whole rock. It is found in coarse pegmatites and also in aphanitic porphyries.

Corundum also occurs in crystalline schists of various kinds, and in metamorphosed limestones. It is developed in belts of contact metamorphism. With magnetite corundum in the form called emery occurs in veins or in layers in crystalline schists.

Resemblances.—Colorless corundum resembles quartz, nephelite, and apatite in double refraction, but is distinguished from these minerals by its higher index of refraction.

Laboratory Production.—Corundum has been obtained in open crucibles upon heating feldspathic rock magmas with an excess of alumina (Morozewicz). It has been obtained by fusing nephelite and leucite. It has been produced in a variety of instances by employing fluxes of different kinds, chiefly with the aid of fluorine compounds.

HEMATITE.

Fe_2O_3.

Composition.—Ferric oxide, $Fe_2O_3 = O\ 30, Fe\ 70 = 100$. Sometimes contains titanium and magnesium, passing in composition into ilmenite. Soluble in concentrated hydrochloric acid. Alters into limonite, less often into magnetite and pyrite.

Trigonal. Scalenohedral class; $c = 1.36557$, $rr' = 94° 0'$.

Euhedral crystals exhibit a great variety of planes; the commoner habit in rocks is tabular parallel to $c(0001)$, often quite thin, six-sided, bounded by $r(10\bar{1}1)$, $a(11\bar{2}0)$, or by $m(10\bar{1}0)$ (Fig. 1) and

other planes, $d(10\bar{1}2)$, $e(01\bar{1}2)$, $n(22\bar{4}3)$. The plates are often irregularly outlined. They are sometimes grouped in rosettes (Fig. 2), and in other cases aggregated in skeleton forms, as in certain micas in which they lie between the laminæ and are so thin as to be transparent. Hematite is in some cases granular or earthy.

Twinning plane $(00\bar{1}1)$ in penetration twins; also with the composition plane perpendicular to (0001). Another mode of twinning has the unit rhombohedron $(10\bar{1}1)$ as the twinning and composition

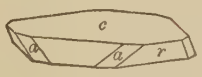


Fig. 1.

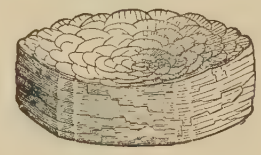


Fig. 2.

plane, usually in polysynthetic laminæ, producing striations on (0001) and a parting parallel to $(10\bar{1}1)$.

Cleavage, or probably only parting due to lamellar twinning, parallel to (0001) and $(10\bar{1}1)$, the unit rhombohedron, whose faces are nearly 90° to each other (94°). Fracture subconchoidal to uneven. Brittle in compact form; elastic in thin laminæ. H.=5.5–6.5. Sp. gr.=4.9–5.3; of crystals mostly 5.20–5.25.

Optical Properties.—Uniaxial, optically negative (−); refraction and double refraction high.

Elba, $\omega_y=3.22$, $\epsilon_y=2.94$, $\omega-\epsilon=0.28$, Wülfing.

Translucent only in extremely thin sections. Color deep red, through yellowish red, to yellowish gray. Pleochroism in sections perpendicular to basal plane: *O* brownish red, *E* yellowish red. Color in crystals black to dark steel-gray; when earthy, red. Streak cherry-red to reddish brown. Luster metallic, occasionally splendent, sometimes dull.

Modes of Occurrence.—Hematite is of widespread occurrence in all kinds of rocks, both as a primary constituent and as a product of alteration. In igneous rocks it forms opaque crystals and anhedrons to some extent in the persalic rocks—granites, syenites, and their lava forms, rhyolite, trachyte—and in some phonolites and andesites, being easily mistaken for magnetite. It also forms inclusions within the other minerals, sometimes in great abundance as in some feldspars (sunstone), and in haüynite in the haüynite-bearing rocks. As a secondary mineral it forms thin films and particles or larger aggregations, and is a common alteration-product of most

iron-bearing minerals. Its occurrence in the crystalline schists is similar to that in the igneous rocks. It gives a red and brown color to many rocks.

Laboratory Production.—Hematite in crystals has been formed by the action of steam on ferric chloride at red heat, which may have been its mode of formation in some volcanic vents, as at Vesuvius. It has been produced from a solution of ferric oxide in molten borax, sodium chloride, or calcium chloride. It has also been formed in a closed tube by heating ferric hydroxide in water with a trace of ammonium fluoride at 250° C.

ILMENITE.

$FeTiO_3$ or $(Fe,Ti)_2O_3$.

Composition variable. If $FeTiO_3 = FeO \cdot TiO_2$, then FeO 47.3, TiO_2 52.7 = 100. But there is an isomorphous series $(Fe,Ti)_2O_3$ with variable amounts of iron and titanium grading to hematite. In some varieties magnesium is present, as in picrotitanite, containing 10–15 per cent. of MgO; in others manganese, forming an isomorphous series to pyrophanite.

Alteration.—Not acted on by acids. In rocks ilmenite commonly alters to a whitish, yellowish, or brownish aggregate, which is highly refracting, and when transparent is seen to be highly doubly refracting. It has been called *leucoxene* by Gümbel, and appears to have a different composition in different cases. It has been identified as titanite by Cathrein, as anatase by Diller, as perovskite by Popoff. Ilmenite alters to carbonate with the separation of rutile that may have been present as inclusions, or may have developed from the titanium in ilmenite. This mode of alteration appears to be confined to certain phyllite formations.

Trigonal. Trirhombohedral class; $c = 1.38458$, $rr' = 94° 29'$. Euhedral crystals commonly tabular parallel to (0001), with six-sided outline, bounded by $r(10\bar{1}1)$, $s(02\bar{2}1)$, also $c(01\bar{1}2)$, sometimes $m(10\bar{1}0)$ and $a(11\bar{2}0)$ (Figs. 1, 2). Less often in steep rhombohedral forms. Usually in thin plates like hematite, elongated to blade-like shapes. Anhedral or subhedral forms are rounded or irregularly outlined, sometimes in skeleton-like aggregates, granular or in minute particles.

Twinning, as in hematite, lamellar parallel to (0001) or $(10\bar{1}1)$. Cleavage not developed. Parting parallel to twinning planes often

shown in partly altered crystals. Fracture conchoidal. H.=5–6. Sp. gr.=4.5–5.

Optical Properties.—Opaque, except in the thinnest flakes or microscopic crystals, when it is clove-brown. Refraction and double refraction not yet determined, but high. Color in opaque crystals

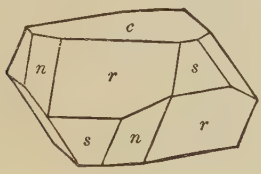


Fig. 1.

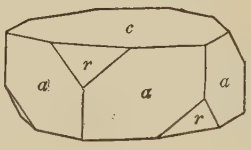


Fig. 2.

iron-black. Streak black to brownish red and submetallic. Luster metallic to submetallic.

Modes of Occurrence.—Ilmenite is a common constituent in igneous rocks from granite to gabbro and related rocks and their lava forms. It has the same mode of occurrence in these rocks as magnetite and hematite. It often forms abundant inclusions in the feldspars and pyroxenes of gabbros, anorthosites, and other basic rocks. Ilmenite occurs similarly in gneiss, mica-schist, and amphibolite.

Resemblances.—Ilmenite in rocks closely resembles hematite and magnetite. As there is a gradation of minerals between ilmenite and hematite in composition, and since magnetite may contain various amounts of titanium, the discrimination of these minerals in rock sections is not always possible. Ilmenite is distinguished from hematite by its different color when thin, or in streak, and by its resistance to acids. Ilmenite is distinguished from magnetite by its behavior toward acids and its feeble magnetism. But titaniferous magnetite can be distinguished only by its crystal form when euhedral.

Pyrophanite, $MnTiO_3$, and *geikielite*, $MgTiO_3$, are rare minerals probably isomorphous with ilmenite, which are not yet to be reckoned among the rock-making minerals. Pyrophanite is found at the Harstig Mine, Pajsberg, Sweden; geikielite occurs in association with precious stones at the mines at Rakvana, Ceylon.

PSEUDOBROOKITE.

$Fe_4(TiO_4)_3$ (?).

Composition probably as given above, or $2Fe_2O_3 \cdot 3TiO_2$. Fe_2O_3 57.1, TiO_2 42.9 = 100. Sometimes with MgO. Decomposed partly by boiling hydrochloric acid, wholly by sulphuric acid.

Orthorhombic; $a:b:c = 0.87776:1:0.88475$. Euhedral crystals commonly minute and tabular parallel to $a(100)$, often prismatic parallel to the b axis. Forms $a(100)$, $b(010)$, $c(001)$, $m(110)$, $e(130)$, $\mu(201)$, and others (Fig. 1). Anhedral crystals rare.

Cleavage (001) distinct. Fracture uneven to subconchoidal H. = 6. Sp. gr. = 4.390 Cederström, 4.98 Koch.

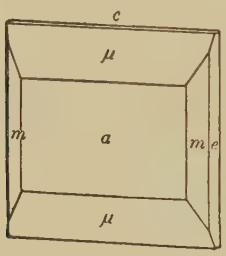


Fig. 1.

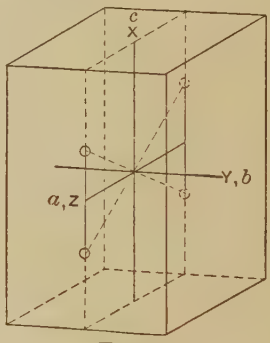


Fig. 2.

Optical Properties.—Plane of the optic axes parallel to (010). Acute bisectrix Z perpendicular to (100). Optically positive (+) (Fig. 2). Axial angle. $2H = 84° 30'$, Lattermann. $v > \rho$. Index of refraction and double refraction strong.

Color.—Dark brown to black, nearly opaque. In very thin sections brownish to ruby-red by transmitted light; slightly pleochroic. Luster adamantine, on fracture greasy.

Modes of Occurrence.—Pseudobrookite is found in small amounts in various igneous rocks, as with hypersthene in cavities in andesite of Aranyer Berg, Transylvania, and in andesite of Behring's Island; in trachyte on Mt. Dore, Puy-de-Dôme; and from Fayal and St. Miguel; in nephelite-basalt of Katzenbuckel; in recent lava (1872) from Vesuvius and elsewhere.

Resemblances.—Pseudobrookite is like brookite, from which it is distinguished by its crystal habit, weak pleochroism, and by chemical tests.

SPINEL GROUP.

$\overset{II}{R}\overset{III}{R}_2O_4$ or $\overset{II}{R}O \cdot R_2O_3$.

$\overset{II}{R}$ = Fe,(Mn),Mg,Zn.

$\overset{III}{R}$ = Fe,(Mn),Al,Cr.

The following minerals of the spinel group occur as rock constituents:

Magnetite,	$FeO \cdot Fe_2O_3$.
Magnesioferrite,	$MgO \cdot Fe_2O_3$.
Franklinite,	$(Fe,Zn,Mn)O \cdot (Fe,Mn)_2O_3$.
Jacobsite,	$(Mn,Mg)O(Fe,Mn)_2O_3$.
Chromite,	$FeO \cdot Cr_2O_3$.
Spinel,	$MgO \cdot Al_2O_3$.
Ceylonite (pleonaste),	$(Mg,Fe)O \cdot Al_2O_3$.
Picotite,	$(Mg,Fe)O \cdot (Al,Fe,Cr)_2O_3$.
Hercynite,	$FeO \cdot Al_2O_3$.
Gahnite,	$ZnO \cdot Al_2O_3$.

These minerals form an isomorphous series of mixed salts, of which certain simpler compounds have received definite names. The commoner varieties are ferrates, aluminates, and chromates of iron and magnesium. The rarer ones contain manganese and zinc. They crystallize in the cubical system, and euhedral crystals are usually octahedrons (111), less often dodecahedrons (110), or combinations of these, rarely more complex forms. They are never cubes. Twinning is similar in all varieties, (111) being twinning and composition plane. Owing to their diverse compositions and modes of occurrence, they will be described in subgroups according to certain degrees of similarity.

MAGNETITE.

Fe_3O_4 or $FeO \cdot Fe_2O_3$.

Chemical Composition.—Iron ferrate. FeO 31.0, Fe_2O_3 69.0 = 100. Ferrous iron sometimes replaced by magnesium and manganese, rarely by nickel; also in part titaniferous. A magnesian variety from Mourne Mountains, Ireland, contains 6.45 MgO; one from New Zealand, 7.15 MgO. A mangan magnetite from Vester Silfberg

contains 6.27 MnO. Titanium oxide in variable amounts up to 25 per cent. has been found in magnetite crystals.

Alteration.—Soluble in hydrochloric acid. Alters to hematite and limonite, also to the carbonate, siderite. When titaniferous, its alteration is sometimes accompanied by the formation of leucoxene.

Isometric. Euhedral crystals commonly octahedrons (111) (Fig. 1), also in dodecahedrons (110) (Fig. 2), striated parallel to the longer

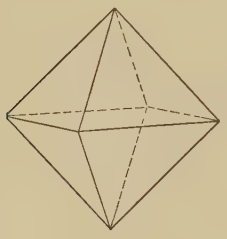


Fig. 1.

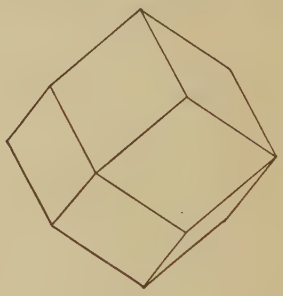


Fig. 2.

diagonal of the crystal face or the combination edge of (111) (110) (Fig. 3). Sometimes combinations of these forms. Other forms rare. Microscopic crystals in glassy rocks often in dendritic aggregates, also as inclusions in some micas. Anhedral crystals of irregular shapes, granular to minute particles.

Twinning.—Octahedral face (111), twinning and composition

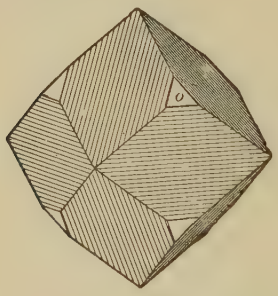


Fig. 3.

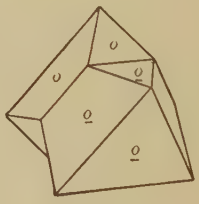


Fig. 4.

plane (Fig. 4) sometimes in polysynthetic lamellæ, producing striations on surface and parting or pseudo-cleavage.

Cleavage not distinct; parting octahedral, often well developed. Fracture subconchoidal to uneven. Brittle. H.=5.5–6.5. Sp. gr.=5.168–5.180 on crystals. Strongly magnetic.

Optical Properties.—Opaque, except in thinnest possible flakes or plates as inclusions in mica, when it is pale brown to black. Streak black. Luster metallic and splendent to submetallic and dull.

Inclusions.—In the igneous rocks magnetite frequently incloses apatite, zircon, and less often the silicate minerals. Chemical investigation has shown that magnetite often incloses ilmenite, which is intergrown with magnetite so that the basal plane of ilmenite is parallel to the octahedral plane of magnetite, that is, the trigonal axes in both minerals are parallel. In some cases rutile needles lie parallel to the octahedral edges. These inclusions are disclosed upon dissolving the magnetite in acid.

Modes of Occurrence.—Magnetite occurs widespread in metamorphic and igneous rocks, but is rare in sedimentary rocks. It often forms large bodies of igneous origin, and others of metamorphic origin. It is almost universally present in igneous rocks, in variable amounts. As a primary constituent it occurs in euhedral and also in anhedral crystals, usually among the earliest pyrogenetic minerals, inclosing or intimately associated with apatite and zircon, and frequently inclosed in the ferromagnesian silicates. It is sometimes to be reckoned among the phenocrysts of porphyritic rocks, and also among the constituents of the groundmass in microscopic crystals. In some phaneric basic rocks, peridotites, it is the latest crystallization, forming a matrix for olivine and pyroxene, as in koswite from Perm, Northern Ural Mountains. In the intersertal parts of some dolerites it forms dendritic aggregates. It is developed in minute crystals in the opaque borders and paramorphs of hornblende and biotite in many lavas. Magnetite is widespread in small amounts in the crystalline schists, sometimes forming large masses by the metamorphism, deoxidation, and dehydration of deposits of limonite and hematite.

Resemblances.—Magnetite resembles hematite, ilmenite, chromite, and graphite, from which it may be distinguished by its strong magnetism and ready solubility in acids. Partly altered titaniferous magnetite in which a development of leucoxene takes place in layers parallel to octahedral planes of parting still further increases the resemblance to ilmenite, for the traces of this parting on octahedral planes intersect at 60° and 120° about a trigonal axis, in the same manner as the traces of rhombohedral parting on the basal plane in ilmenite.

Laboratory Production.—Magnetite has been produced in open crucibles upon the cooling of silicate solutions containing iron; also

in furnace slags. It has been formed in crystals by the action of hydrochloric acid on heated ferric oxide, by the action of iron on alkaline sulphates, and by other methods.

MAGNESIOFERRITE.

$MgFeO_4 = MgO \cdot Fe_2O_3$.

Composition.—Magnesium ferrate. MgO 20, Fe_2O_3 80 = 100. Difficultly soluble in hydrochloric acid.

Isometric.—Octahedrons, and octahedrons modified by the dodecahedron. H. = 6 – 6.5. Sp. gr. = 4.568 – 4.654. Strongly magnetic.

Color, streak, and luster as in magnetite. Occurs about fumaroles of Vesuvius, and especially those of the eruption of 1855, associated with crystals of hematite.

Formed in the laboratory by heating together Fe_2O_3 and MgO in the presence of hydrochloric acid vapor.

FRANKLINITE.

$(Fe,Zn,Mn)O \cdot (Fe,Mn)_2O_3$.

JACOBSITE.

$(Mn,Mg)O \cdot (Fe,Mn)_2O_3$.

Composition.—Franklinite and jacobsite are ferromanganates of iron, manganese, zinc, or magnesium, varying in proportions, and may be looked upon as magnetite in which Mn, Zn, or Mg replaces ferrous iron to various extents, and Mn in part replaces ferric iron. Both minerals are soluble in hydrochloric acid, sometimes with the evolution of a small amount of chlorine.

The crystal forms and habits of both minerals are the same as those of magnetite. The same is true of the parting or pseudo-cleavage and fracture. H. = 5.5 – 6.5 franklinite, 6 jacobsite. Sp. gr. = 5.07 – 5.22 franklinite, 4.75 jacobsite. Franklinite is slightly magnetic, jacobsite is magnetic.

Color of each is black, streak of franklinite reddish brown or black, that of jacobsite blackish brown. Luster metallic, sometimes dull in franklinite, brilliant in jacobsite.

Modes of Occurrence.—Franklinite occurs in coarsely crystalline calcite associated with zinc silicate, willemite, and other zinc and

manganese minerals at Franklin Furnace and at Sterling Hill, N. J., and elsewhere. Jacobsite occurs in a crystalline limestone with white mica and native copper at Jakobsberg, in Nordmark, and also with tephroite and calcite at Långban, Sweden.

Resemblances.—A distinction of these minerals from magnetite rests chiefly on chemical tests, the determination of the presence of Mn and Zn.

Franklinite has been formed in the laboratory by the action of ferric chloride and zinc chloride on lime with heating.

CHROMITE.

$FeO \cdot Cr_2O_3$.

Composition.—Iron chromate. Cr_2O_3 68, FeO 32 = 100. The iron may be replaced in part by magnesium, the chromium by aluminium and ferric iron. Such varieties form transitions to picotite, a chrome spinel. Not acted on by acids.

Isometric. Euhedral crystals rare, octahedrons, sometimes modified by the dodecahedron, and (311). Commonly anhedral, massive, granular.

Cleavage not recognizable. Fracture uneven. Brittle. H. = 5.5. Sp. gr. = 4.32 – 4.57. Sometimes feebly magnetic.

Optical Properties.—Translucent to opaque. Color between iron-black and brownish black. In extremely thin flakes brown, red-brown to yellowish red. Refraction high. $n = 2.0965$ as calculated by Thoulet from angle of total polarization. Luster submetallic to metallic.

Modes of Occurrence.—Chromite is a pyrogenetic mineral in igneous rocks, especially those rich in olivine, enstatite, as the peridotites, and other basic varieties, both phanerocrystalline and aphanitic. Hence it is often found in serpentine. Its occurrence in these rocks is similar to that of magnetite. It is also found in some meteorites. Chromite occurs in the more magnesian crystalline schists, sagvandite, listwänite, amphibolite. It also occurs in some dolomites, as at Hoboken, N. J.

Resemblances.—Chromite is most like picotite, from which it can be distinguished only by its lower hardness and higher specific gravity.

SPINEL.
$MgO \cdot Al_2O_3$.

CEYLONITE.
$(Mg,Fe)O \cdot Al_2O_3$.

PICOTITE.
$(Mg,Fe)O \cdot (Al,Fe,Cr)_2O_3$.

Composition.—Magnesium aluminate, with the magnesium partly replaced by iron in ceylonite or pleonaste; and in addition the aluminium partly replaced by iron and chromium in picotite. Ferric iron may be present in small amounts in the first-named varieties. Picotite is intermediate in composition between spinel and chromite. Not acted on by hydrochloric acid. Soluble with difficulty in concentrated sulphuric acid, more readily in proportion to the amount of iron present.

Alteration.—Commonly unaltered, even when the associated minerals are more or less completely altered. It has been altered to muscovite in the cyanite-gneiss and amphibolite of Neustadt in the Black Forest. Also known to alter to talc (steatite), serpentine, and hydrotalcite.

Crystal Forms.—Isometric. Usually in octahedrons, sometimes modified by the dodecahedron and other forms; rarely in cubes. Also in rounded and subangular crystals.

Twinning plane and composition plane the octahedral face. Sometimes repeated in polysynthetic lamellæ.

Cleavage imperfect parallel to (111). Fracture conchoidal. Brittle. H. = 8. Sp. gr. variable with the composition: 3.52–3.58 and 3.63–3.71 magnesia spinel, 3.5–3.6 ceylonite, 4.08 picotite.

Optical Properties.—Transparent to nearly opaque in megascopic crystals. Colors: red of various shades, yellow, violet to blue in ruby spinel or magnesia spinel; green, brown to black in ceylonite or pleonaste; grass-green in chlorospinel, owing to the presence of copper; dark yellowish brown to greenish brown in picotite. In thin sections the colors are lighter shades. Index of refraction high, varying with the composition and depth of color. Luster vitreous; splendent to nearly dull.

Spinel, red, Ceylon:	$n_r = 1.7121$	$n_y = 1.7135$	$n_b = 1.7261$		Des Cloizeaux
		$n_y = 1.7150$			Rosenbusch
		$n = 1.7167$			Zimanyi
" blue, "	$n_r = 1.7153$	$n_y = 1.7188$	$n_b = 1.7227$		Melczer
	$n_r = 1.7171$	$n_y = 1.7201$	$n_b = 1.7272$		Bauer
	$n_r = 1.7206$	$n_y = 1.7257$	$n_{gr} = 1.7323$		Busz
" " Åker		$n_y = 1.7200$			Zimanyi

Modes of Occurrence.—*Picotite*, which is a variety intermediate between spinel and chromite, is yellow and brown in minute crystals, and has quite the same mode of occurrence as chromite, in basic igneous rocks, peridotites and their corresponding porphyries, and in serpentine derived from them. It is found also in highly magnesian members of the crystalline schists.

Ceylonite or *pleonaste* is green, and occurs occasionally with magnetite in igneous rocks. It has been found in granite and some nephelite-syenite, in sanidinite of the Laacher See, in mica-andesite at the Cascade de Tourci, in the Cantal, and in lherzolite in Piedmont. It is common in metamorphic rocks, both the crystalline schists and in zones of contact metamorphism. It is especially developed in metamorphosed limestones with silicate minerals of various kinds. Thus in granular limestone inclosed in gneiss at Mereus and Arignac, on the borders of l'Ariège, it is associated with brucite, chondrodite, scapolite, pyroxene, etc; similarly at Warwick, N. Y., and in the vicinity of Amity, N. Y., and at many other localities. It is commonly developed in dolomite by contact metamorphism, as at Monzoni in the Tyrol; also in blocks of limestone inclosed in lava, as at Vesuvius.

Spinel proper, magnesia spinel, or precious spinel, which is red, blue, pale green, or colorless, occurs chiefly in metamorphosed granular limestone and dolomite, and in other members of the crystalline schists.

Resemblances.—*Picotite* most closely resembles chromite, from which it can be distinguished only by its hardness, specific gravity, or chemical composition. *Ceylonite* (pleonaste) is most like hercynite, being distinguishable only by chemical analysis. *Spinel* proper resembles some light-colored garnets, which have a somewhat higher index of refraction. Similarly picotite and chromite resemble some brown garnets. The two kinds of minerals are distinguishable by their differences in specific gravity and by the presence of silicon in garnet.

Laboratory Production.—Spinel has been produced by various processes in the laboratory: by heating a mixture of alumina and magnesia with boracic acid, a red color has been introduced by adding oxide of chromium; also by heating fluorides of aluminium and magnesium with boracic acid; also by heating magnesium hydrate with aluminium chloride in the presence of water vapor; and by other methods.

HERCYNITE.

$FeO \cdot Al_2O_3$.

Composition.—Iron aluminate. FeO 41.4, Al_2O_3 58.6 = 100. The iron may be replaced to some extent by magnesium, making a transition to ceylonite. Not acted on by acids.

Isometric. Anhedral, massive, fine granular. H. = 7.5–8. Sp. gr. = 3.91–3.95.

Color.—Black. Streak dark grayish green to leek-green. In thin section sap-green. Index of refraction high. $n = 1.749$, Lévy-Lacroix. Luster vitreous.

It occurs in the granulites of Saxony in streaks associated with garnet, quartz, sillimanite, and feldspar; also with corundum and iron hydroxide at Ronsberg, Böhmerwald. A magnesium-bearing variety is found with corundum and magnetite in Cortlandt township, N. Y. Hercynite closely resembles ceylonite, from which it is distinguished by its specific gravity and chemical composition.

GAHNITE.

$ZnO \cdot Al_2O_3$.

Composition.—Zinc aluminate. ZnO 44.3, Al_2O_3 55.7 = 100. Zinc may be replaced in part by Fe, Mn, Mg, and aluminium in part by ferric iron, yielding the varieties:

Automolite, $ZnO \cdot Al_2O_3$ with sometimes a little iron.

Dysluite, $(Zn,Fe,Mn)O \cdot (Al,Fe)_2O_3$.

Kreittonnite, $(Zn,Fe,Mg)O \cdot (Al,Fe)_2O_3$.

Insoluble in hydrochloric acid. Soluble with difficulty in concentrated sulphuric acid.

Crystal Forms.—Isometric. Euhedral crystals commonly octahedrons, sometimes in dodecahedrons and modified cubes. Also in anhedral crystals. Twinning, cleavage, and fracture the same as in spinel. H. = 7.5–8. Sp. gr. = 4–4.6 in automolite and dysluite, 4.48–4.89 in kreittonnite.

Optical Properties.—Subtransparent to nearly opaque in megascopic crystals. Color green in various shades and tones to greenish black, bluish black, yellowish, or grayish brown. Streak grayish. In thin sections and minute crystals green or yellow and brown.

Index of refraction high. $n = 1.765$, Lévy-Lacroix. Luster vitreous or somewhat greasy.

Modes of Occurrence.—*Gahnite* occurs sparingly in the crystalline schists. *Automolite* occurs in talcose schist at Falun, Sweden; at Minas Geraes, Brazil; at Franklin Furnace, N. J., with franklinite and willemite in calcite; with feldspar in Delaware County, Pa., and with mica in Mitchell County, N. C. *Dysluite* is found with franklinite in calcite at Sterling, N. J. *Kreittonnite* at Bodenmais, Bavaria.

Resemblances.—Gahnite is most like other green and brown spinels, from which it is distinguishable only by chemical means.

Laboratory Production.—Gahnite has been produced together with tridymite in the porous muffles of zinc furnaces, through a reaction of the zinc vapors with the aluminous material of the furnace hood at a temperature of about 1300° C. It has also been formed in a fayalite slag at the Freiberg furnaces.

PERICLASE.

MgO.

Composition.—Magnesia. Iron and manganese may also be present, and sometimes zinc. The pulverized mineral gives an alkaline reaction when moistened, and dissolves in mineral acids without effervescence. Alters to hydromagnesite in fibrous and spherulitic aggregation, also to serpentine and brucite. It has been suggested by Tschermak that the cubically cleaved serpentine from Tilly Foster Mine, Brewster County, N. Y., is altered periclase.

Isometric.—Euhedral crystals in cubes or octahedrons; also anhedral and rounded forms. Cleavage perfect parallel to the cube, less distinct parallel to the octahedral face. H. = 6 nearly. Sp. gr. = 3.674 Vesuvius, with FeO 6 per cent.; 3.90 Nordmark, with MnO 9 per cent. and ZnO 2 per cent.

Optical Properties.—Transparent to translucent, colorless to grayish, yellow to brownish yellow, and dark green. Index of refraction high. On artificial crystals, $n = 1.7307$, $n_y = 1.7364$, $n_{gr} = 1.7413$, Mallard.

Modes of Occurrence.—Periclase occurs in metamorphosed limestone, sometimes with forsterite and earthy magnesite, inclosed in the lavas of Mte. Somma, Vesuvius. It is found with hausmannite in dolomitic limestone in Nordmark, Sweden, and in the zone of contact metamorphism in dolomite near Predazzo, Tyrol.

Resemblances.—Periclase is like pale-colored and colorless garnet in refraction, but differs from it in the cubical habit of some of its euhedral crystals and in its cubical cleavage.

Laboratory Production.—Periclase has been formed by the action of lime on magnesium borate at a high temperature, by the action of hydrochloric acid gas on magnesia, and by the action of magnesium chloride on lime. It has also been crystallized in octahedrons from a fused solution of magnesia in caustic potash.

ICE.

H_2O.

Composition.—Oxygen 88.9, hydrogen 11.1 = 100.

Hexagonal, (?) pyramidal; $c = 1.4026$ approx.

Euhedral crystals rare; commonly in skeleton forms of growth as in snow-crystals. Observed planes (0001), $(10\bar{1}0)$, less often $(10\bar{1}2)$, $(10\bar{1}1)$, $(40\bar{4}1)$. Usually tabular parallel to the base (0001), with very subordinate prism and rhombohedral planes, giving hexagonal outline. Sometimes in hexagonal prisms $(10\bar{1}0)$ combined with the basal plane (0001). Rhombohedral crystals very rare. Anhedral crystals bladed, acicular, granular.

Gliding plane parallel to (0001) developed under pressure. Brittle at low temperatures, less so near melting-point. Fracture conchoidal. H. = 1.5. Sp. gr. = 0.9167, Bunsen.

Optical Properties.—Uniaxial; optically positive (+); refraction very low, double refraction low.

$\omega_r = 1.30598$	$\omega_{gr} = 1.3120$	$\omega_v = 1.317$	Reusch
$\epsilon_r = 1.30734$	$\epsilon_{gr} = 1.3136$	$\epsilon_v = 1.321$	
$\epsilon - \omega = 0.00136$	0.0016	0.004	

$\omega_r = 1.2970$ at $-8°$ C.	$\omega_y = 1.3090$ at $-8°$ C.	$\omega_{gr} = 1.3107$ at $-3.8°$ C.	Meyer
$\epsilon_r = 1.3037$ "	$\epsilon_y = 1.3133$ "	$\epsilon_{gr} = 1.3163$ "	"
$\epsilon - \omega = 0.0067$	0.0043	0.0056	

Colorless to white when pure. In thick masses pale blue.

Occurrence.—Ice is familiar in the form of snow in tabular stellate and hexagonal crystals of great delicacy and beauty, less often in minute hexagonal prisms terminated by the basal pinacoid; also as frost-crystals, and on window-panes in acicular, dendritic, plumose, stellate, and other forms of aggregation; as hail in dense aggregates of anhedral crystals; as ice on bodies of water in large

acicular crystals forming irregularly arranged aggregates, or in solid masses composed of large hexagonal crystals whose prismatic axis c is normal to the surface of the sheet of water.

In glaciers the ice crystals are commonly irregularly shaped anhedrons, sometimes more or less laminated or roughly tabular, similar in character to crystals of calcite in granular limestone.

DIASPORE.

AlO(OH).

Composition.—Hydrous oxide of aluminium, $Al_2O_3 \cdot H_2O$. Al_2O_3 85.0, H_2O 15.0 = 100. Not attacked by acids.

Orthorhombic; $a:b:c = 0.93722:1:0.60387$.

Euhedral crystals prismatic, usually thin, flattened parallel to (010), sometimes acicular, faces often rounded. Forms developed, b(010), m(110), h(210), l(120), and other prisms of this kind, e(011), s(212), q(232), and other bipyramids (Figs. 1 and 2).

Cleavage parallel to (010) eminent; parallel to (210) less perfect. Fracture conchoidal. Very brittle. H. = 6.5–7. Sp. gr. = 3.3–3.5

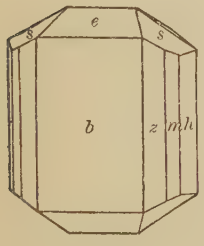


Fig. 1.

Fig. 2.

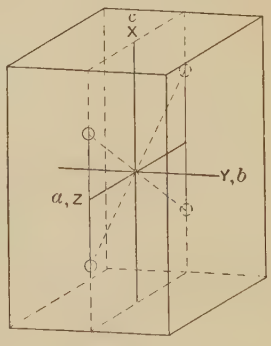


Fig. 3.

Optical Properties.—Optically positive (+). Acute bisectrix Z perpendicular to (100). Axial plane parallel to (010). $X \parallel c$, $Y \parallel b$, $Z \parallel a$; $2V_r = 84° 8'$ (Fig. 3), $2V_y = 84° 20'$, $2V_v = 85° 8'$, Des Cloizeaux. $2V = 84°$-$85°$, Schemnitz, Lévy-Lacroix. Dispersion feeble, $\rho < v$. Index of refraction moderately high.

$\beta_r = 1.719$, $\beta_y = 1.722$, $\beta_v = 1.729$, Des Cloizeaux.

$\alpha = 1.702$, $\beta = 1.722$, $\gamma = 1.750$, $\gamma - \alpha = 0.048$, Schemnitz, Lévy and Lacroix.

Color.—Whitish, grayish, greenish gray, hair-brown, yellow to colorless; sometimes pleochroic, violet-blue in one direction, plum-blue in another, pale asparagus-green in a third. In diaspore from Bournac, Haute-Loire, Lacroix found $X=Y$ colorless, Z blue. In thin section colorless to pale colored in the tints above named; pleochroism not noticeable. Luster vitreous, pearly on cleavage surface.

Occurrences.—Diaspore is closely associated with corundum and emery in dolomite, chlorite-schist, and other crystalline rocks, near Kossoibrod, Ural; at Schemnitz, Hungary; and in various other localities in Europe. It occurs with corundum and margarite near Unionville, Chester County, Pa.; at the Emery Mines of Chester, Mass., and elsewhere in the United States. It has been found in the nephelite-syenites of Norway; in the altered trachyte of Mount Robinson, Rosita Hills, Colo.; in gneiss and granite inclusions in basalt tuff of Bournac, Haute-Loire.

Resemblances.—Diaspore is like sillimanite and andalusite, but has somewhat higher refraction and much stronger double refraction. In sillimanite the prismatic axis is the direction of vibration of the slow ray, Z. In andalusite the double refraction is much lower.

HYDRARGILLITE (Gibbsite).

$Al(OH)_3$.

Composition.—Aluminium hydrate, $Al_2O_3 \cdot 3H_2O = Al_2O_3$ 65.4, H_2O 34.6 = 100. Soluble in concentrated sulphuric acid.

Monoclinic; $a:b:c = 1.70890:1:1.91843$, $\beta = 85° 29\frac{1}{6}'$.

Euhedral crystals tabular parallel to (001), with (001)(100) and (110), hence hexagonal in appearance, since $(110)(1\bar{1}0) = 119° 10\frac{1}{2}'$; also $(\bar{1}01)$ and other planes. Anhedral crystals in spherulites of radiating lamellæ; also mammillary and fibrous-scaly.

Twinning plane (001) common, usually combined with a twinning in which (110) or (100) is the twinning plane; also a twinning analogous to that common in mica; and others.

Cleavage parallel to (001) eminent; flexible and tough. Percussion figure similar to that in mica, with the cracks normal to the hexagonal boundary lines. H. = 2.5–3.5. Sp. gr. = 2.287–2.420.

Optical Properties.—Optically positive (+); plane of the optic axes parallel to (010), though in some cases normal to (010). Acute bisectrix Z inclined to the c axis 20° 57′ in the acute angle β, Brögger.

Axial angle variable, from 0°, Langesund, to nearly 40°, Zlatoust. Dispersion strong, $\rho > v$. In crystals from the Ural there is a marked change in the position of the optic axes with change of temperature, Des Cloizeaux. Refraction low, double refraction strong.

Langesund, $\alpha = \beta = 1.5347$, $\gamma = 1.5577$, $\gamma - \alpha = 0.023$, Brögger.

Color.—White, grayish, greenish, or reddish white; also reddish yellow when impure. In thin section colorless. Luster on (001) pearly, on other faces vitreous.

Occurrence.—Hydrargillite accompanies corundum at Gumuch-dagh, Asia Minor, at Unionville, Pa., and elsewhere. It is found with natrolite in nephelite-syenite on Lille Arö and Eikaholm, Langesund fjord; in schist with magnetite near Zlatoust, Ural; as an alteration-product of feldspar in laterite, and in certain basalts altered to bauxite.

Resemblances.—Hydrargillite resembles brucite in refraction, double refraction, and optically positive character. It differs from it in having the acute bisectrix inclined to the basal cleavage, and in being biaxial in some cases. It resembles muscovite somewhat in refraction, but has slightly lower double refraction, more inclined position of the acute bisectrix, smaller optic angle, and different optical character. It resembles kaolinite in refraction, but has much stronger double refraction.

Laboratory Production.—Obtained by de Schutén from a saturated solution of aluminium hydroxide in dilute ammonia by gradual evaporation of the ammonia; also by precipitation from a hot alkaline solution of $Al(OH)_3$ with carbon dioxide.

GOETHITE.

$FeO(OH)$.

Composition.—Hydrous oxide of iron, $Fe_2O_3 \cdot H_2O$. Fe_2O_3 89.9, H_2O 10.1 = 100. Soluble in hydrochloric acid.

Orthorhombic; $a:b:c = 0.9185:1:0.6068$.

Euhedral crystals prismatic with $b(010)$, $m(110)$, $d(210)$, terminated by $p(111)$ and $c(011)$ (Fig. 1). Prisms vertically striated. Often flattened in scales or tables parallel to (010). Also fibrous.

Cleavage parallel to (010) perfect. Fracture uneven. H. = 5–5.5. Sp. gr. = 4.37.

Optical Properties.—The acute bisectrix is X, optically negative (−), and is perpendicular to (010), the cleavage plane. The plane

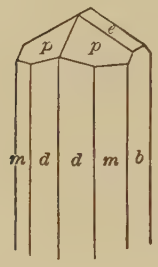


Fig. 1.

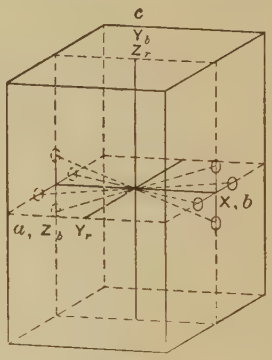


Fig. 2.

of the optic axes for red is parallel to (100), that for green is parallel to (001), at right angles to one another as in brookite (Fig. 2). $2E_r = 58° 31'$, $2E_y = 67° 42'$. The indices of refraction and double refraction are high, $\beta = 2.5$ approx., Pelikan.

Color.—Yellowish, reddish, and blackish brown, often blood-red by transmitted light. Pleochroic: X light brown, Y yellow-brown, Z light orange-yellow, on goethite from Cornwall, Pelikan. Streak brownish yellow to ocher-yellow.

Occurrence.—Goethite occurs in films, scales, and minute particles as inclusions in the rock-making minerals. It also occurs commonly with other oxides of iron, especially hematite and limonite.

Resemblances.—Goethite resembles brookite and pseudobrookite, but is distinguished by being optically negative, more pleochroic, and by its behavior toward acid. It is distinguished from hematite by its biaxial character and optical behavior in the plane of lamination, (010) in goethite, (0001) in hematite.

BRUCITE.

$Mg(OH)_2$.

Composition.—Magnesium hydrate. MgO 69, H_2O 31 = 100. Iron and manganese are sometimes present. Soluble in acids without effervescence. Alters to hydromagnesite, also to serpentine.

Trigonal, scalenohedral; $c = 1.52078$.

Euhedral crystals usually tabular parallel to $c(0001)$, with the unit rhombohedrons $(10\bar{1}1)$, and other plus and minus rhombohedrons. Commonly anhedral in irregularly bounded scales and foliated masses; also fibrous, the fibers separable and elastic.

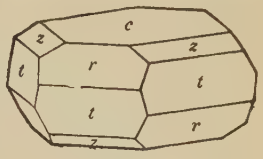


FIG. 1.

Cleavage basal (0001), eminent. Laminæ flexible. Sectile. It yields a six-rayed percussion figure like that in mica and talc, parallel to the rays of which the crystal may be easily bent. H. = 2.5. Sp. gr. = 2.388, Ural.

Optical Properties.—Uniaxial, sometimes anomalously biaxial. Optically positive (+). Index of refraction moderate, $\omega_r = 1.559$, $\epsilon_r = 1.5795$, Bauer. $\epsilon - \omega = 0.0205$. Double refraction strong, about as in pyroxene. Color white to grayish, bluish, or greenish. In thin section colorless to greenish. Luster on cleavage surface pearly, elsewhere waxy to vitreous.

Modes of Occurrence.—Brucite is occasionally found in phyllites and schists, especially those containing carbonates; also in limestone and in serpentine accompanying other magnesian minerals.

Resemblances.—Brucite resembles talc, muscovite, and gypsum, from which it differs by being uniaxial and optically positive, and by its solubility in acids. Fibrous brucite resembles hydromagnesite, but is distinguished by its higher double refraction and the absence of effervescence upon solution in acids.

Laboratory Production.—Brucite has been obtained from a solution of magnesium chloride precipitated by an excess of caustic potash and heated to 200°; the brucite crystals separate on cooling. It has also been noticed in crystallized plates as a deposit in a steam-boiler.

FLUORITE.

CaF_2.

Composition.—Calcium fluoride. Ca 51.1, F 48.9 = 100. With sulphuric acid decomposed with liberation of hydrofluoric acid vapor. Scarcely attacked by other acids. Alteration-products seldom observed in rocks.

Isometric. Euhedral crystals commonly cubes, less often octahedrons, rarely developed within rocks. Commonly anhedral, filling cavities or cracks, or the spaces between other minerals.

Twinning octahedral, not recognizable in rock sections.

Cleavage octahedral perfect. Often highly developed in fluorite in rock sections as numerous straight cracks. Fracture flat conchoidal. H.=4. Sp. gr.=3.180–3.189.

Optical Properties.—In thin sections rock-making fluorite is isotropic. Large crystals grown on the walls of cavities are sometimes doubly refracting. Such crystals are composed of double-refracting laminæ intersecting one another, apparently parallel to the dodecahedral planes. Index of refraction very low, varying somewhat with the color and the locality. $n_y = 1.4336$ (yellow) Gersdorf, 1.4343 (green-violet) Alston Moor, Dudenhausen. The refraction is so much lower than that of Canada balsam that the surface of fluorite appears shagreened in diaphragmed light in the same manner as that of a mineral with moderately high refraction, apatite or hornblende.

Color.—White, yellow, green, red, violet-blue, sky-blue, brown to bluish black. In rock sections usually colorless, violet, blue; sometimes the color varies in zones or in irregularly shaped patches. Luster vitreous, sometimes splendent.

Modes of Occurrence.—Fluorite occurs in all kinds of rocks, usually in small amounts. It is frequently a product of vapor or fumarole action and is deposited in veins or cavities in crystalline schists and sedimentary rocks accompanying quartz, barite, and other vein minerals.

In igneous rocks it is sometimes disseminated through the rock body as though inherent in the rock magma; in other cases it is chiefly distributed near contacts or fissures as though originating in gaseous exhalations. It is often present in small amounts in granites and syenites, and is more abundant in nephelite-bearing rocks in association with fluorine-bearing titano- and zirconosilicates, låvenite, rosenbuschite, etc., especially in the Norwegian nephelite-syenites.

Fluorite is often rich in fluid inclusions.

Resemblances.—Colorless fluorite is similar in its low index of refraction to opal, analcite, and the sodalite minerals. Its bluish-violet color when present is characteristic. It is distinguished from opal by its cleavage, from analcite and the sodalites by its lower refraction tested by diaphragmed light; by its perfection and direction of cleavage; by its resistance to weak acids, and by other chemical tests.

Laboratory Production.—Fluorite has been produced in crystallized forms by Scheerer and Drechsel.

PYRITE.

FeS_2.

Composition.—Iron disulphide. S 53.4, Fe 46.6=100. Sometimes traces of copper, nickel, cobalt, and thallium. Insoluble in hydrochloric acid, decomposed by nitric acid. Alters by oxidation to iron sulphate, and upon loss of sulphur to hematite or limonite.

Isometric; didodecahedral. Euhedral crystals common. Forms usually cubes (100), pentagonal dodecahedrons (210), singly and in combination, also octahedrons (111), and others subordinate. Less often in anhedral crystals or grains and in irregular aggregations.

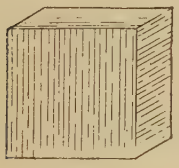


Fig. 1.

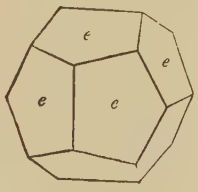


Fig. 2.

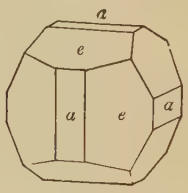


Fig. 3.

Twinning common, dodecahedral plane (110), twinning and composition plane. Not noticeable in thin section.

Cleavage indistinct and rare parallel to (100) and (111), not shown in thin section. Fracture conchoidal to uneven. H.=6–6.5. Sp. gr.=4.967 Traversella, 5.027 Elba.

Optical Properties.—Opaque. Color pale brass-yellow on fresh surface or on cross-section. Streak greenish or brownish black.

Modes of Occurrence.—Pyrite occurs sparingly in all kinds of rocks, igneous, metamorphic, and sedimentary. It is often in isolated crystals; sometimes in clusters, irregular or spheroidal in form, or in flattened spherulites; sometimes in veins. It is commonly associated with iron oxide, magnetite, and hematite, and in the neighborhood of metallic veins it is often accompanied by sulphides of copper, zinc, and lead, such as chalcopyrite, bornite, chalcocite, sphalerite, galena, and others.

Resemblances.—Pyrite is distinguishable from other opaque rock-making minerals by its color in incident light, which is most like that of chalcopyrite, but is not so dark and brass-like. Chalcopyrite gives a strong reaction for copper. Pyrite is distinguished from pyrrhotite by its color and absence of magnetic properties, and by its behavior towards acids.

Laboratory Production.—Pyrite has been produced by slow reduction of ferric sulphate in the presence of some carbonate; also by heating together ferric oxide, sulphur, and ammonium chloride.

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PYRRHOTITE.

Fe_nS_{n+1}.

Composition.—Magnetic pyrite. Sulphide of iron, often containing nickel and traces of cobalt and copper. Variable in composition, ranging from Fe_5S_6 to $Fe_{16}S_{17}$, chiefly $Fe_{11}S_{12}$ = S 38.4, Fe 61.6 = 100. Decomposed by hydrochloric acid with evolution of hydrogen sulphide. Alters to pyrite, limonite, and siderite.

Hexagonal; $c = 0.8701$. Euhedral forms rare, commonly tabular parallel to (0001), with prism $(10\bar{1}0)$ and pyramidal faces $(10\bar{1}1)$, $(20\bar{2}1)$, $(40\bar{4}1)$, and others. Sometimes in steep pyramidal crystals. Usually anhedral, in irregular masses or particles.

Twinning plane $(10\bar{1}1)$, not recognizable in thin section. Cleavage sometimes distinct parallel to the basal plane (0001), less so parallel to the prism of the second kind $(11\bar{2}0)$. Not noticeable in thin sections. Fracture uneven to subconchoidal. H. = 3.5–4.5. Sp. gr. = 4.58–4.64. Magnetic to a variable extent.

Optical Properties.—Opaque. Color between bronze-yellow and copper-red, subject to speedy tarnish. Streak dark grayish black. Luster metallic.

Modes of Occurrence.—Pyrrhotite occurs sparingly in some gabbros, dolerites, basalts, and related rocks, and in metamorphic rocks derived from them, such as amphibole-schists and amphibolites. It is much rarer in the granites and gneisses and in zones of contact metamorphism, but is sometimes abundant in nephelite rocks according to Rosenbusch.

Resemblances.—Pyrrhotite is distinguished from other opaque minerals occurring in rocks by its color, weak magnetism, and chemical reactions.

GRAPHITE.

C.

Carbon, often impure from the presence of iron oxide, clay, etc. Unaltered by acids. At a high temperature some graphite burns more readily than others. Some lamellar varieties, when treated with boiling acid and afterwards ignited, swell up with worm-like

contortions, and have been called *graphitite*. This action is probably due to the vaporization of liquid that has penetrated interlamellar spaces. An impure variety containing nitrogen and water, burning in a Bunsen flame, has been called *graphitoid*.

Trigonal, rhombohedral; $c = 1.3859$.

Crystal Forms (0001), $(11\bar{2}0)$, $(10\bar{1}1)$, $(22\bar{4}6)$, $(11\bar{2}1)$. Euhedral crystals very rare, commonly in six-sided tabular crystals, often striated parallel to the trace of the unit rhombohedron $(10\bar{1}1)$; also in rounded and irregularly shaped plates or flakes, less often columnar or radiated, granular, compact, earthy.

Twinning possibly indicated by the striations on (0001); twinning and composition plane a rhombohedral face.

Cleavage perfect parallel to (0001), the basal pinacoid, possibly indistinct parallel to the unit rhombohedron $(10\bar{1}1)$ or the possible twinning laminæ. This is indicated by the exhibition of a percussion figure with 3 or 6 rays, as in mica, the lines of cleavage or gliding being parallel to the trace of the unit rhombohedron.

Cleavage lamellæ flexible, but inelastic. Feel greasy. H. = 1–2. Sp. gr. = 2.09–2.23, varying with impurities.

Optical Properties.—Opaque in the thinnest particles. Color iron-black to steel-gray. Luster metallic, sometimes dull, earthy.

Modes of Occurrence.—Graphite occurs chiefly in metamorphic rocks, to a much less extent in igneous rocks. It is a constituent of gneisses and schists, and of various contact rocks, as hornstones, crystalline limestones, quartzites, etc. In many cases presumably it has resulted from the alteration of hydrocarbons of organic origin. In others it may have resulted from impregnation by carbon or hydrocarbon vapors. It occurs in disseminated grains, scales, or crystals, or in streaks, layers, or beds in the rocks.

It occurs in gneiss in various localities in Massachusetts, Connecticut, New Hampshire, New York, and elsewhere. It is found in crystalline limestone, associated with titanite and wollastonite, at Grenville, Canada; accompanying spinel, chondrodite, hornblende, etc., near Amity, N. Y.; also in Bucks County, Pa., associated with wollastonite, pyroxene, and scapolite.

In igneous rocks it occurs in disseminated grains and scales in granite, syenite, and similar rocks, and in some pegmatites. It is abundant in syenite at Mansell's Mine in Bucks County, Pa.; in the granites of the Ilmen Mountains; in pyroxene-foyaite from Botogolsky-Goletz, Siberia, which traverses limestone and graphite-schist. It occurs in basalt of Ovifak, Greenland, with metallic iron, and in

nests in trap at Borrowdale in Cumberland, England. It is also a constituent of some meteorites.

Resemblances.—Graphite is distinguished from hydrocarbons by the greater difficulty with which it may be burned, and by the absence of hydrogen and other gases. It resembles molybdenite closely, but is distinguished chemically by the absence of sulphur. It is distinguished from magnetite by crystal form when present, hardness, resistance to the attack of acids, etc.

Laboratory Production.—Graphite is a common product in iron furnaces.

HYDROCARBONS.

Impure mixtures of coal of various compositions, with other hydrocarbons. Unattacked by acids; more or less easily burned.

Amorphous. In particles of irregular shapes and as coatings on the walls of cracks or cavities. H. = 0.5–2.5. Sp. gr. = 1–1.7 approx.

Optical Properties.—Opaque; gray to black. Lusterless on natural surface. Acquires a dull gloss on being rubbed.

Modes of Occurrence.—Hydrocarbons occur in small particles and as coatings or layers in many sedimentary and schistose rocks, in some cases forming inclusions within the constituent crystals of quartz, feldspar, etc. They are frequently accompanied by iron oxide, with which they may be confused. The latter may be removed by hydrochloric or nitric acid, and the hydrocarbon tested by ignition. They are easily confused with graphite. They have been identified by Sauer in the quartzites of the schist and phyllite formations of the Erzgebirge. A graphitoid-like hydrocarbon has been described by Rosenbusch as common in the paragneisses of the Black Forest.

TABLES.

The optical characteristics of the rock minerals are given in the accompanying tables, in which the minerals are arranged in series according to increasing refringence; the isotropic minerals being placed together, followed by the uniaxial, and then the biaxial. They are also grouped mineralogically, and not strictly according to their system of crystallization, since orthorhombic, monoclinic, and triclinic members of one group occur together, as the amphiboles.

The indices of refraction are not averages, but specific examples given in the text. In some instances several sets of data are given for one mineral to indicate the divergence in the observations.

Name.	System.	*n*.	Color.	Remarks.
Opal	amorphous	1.45	colorless	occasionally slightly birefringent.
Obsidian	"	1.484–1.495	"	
Glass from granite	"	1.500–1.510	"	SiO_2 72.65 – 6731
" " syenite	"	1.520	"	" 60.26
" " monzonite	"	1.550	"	" 53.75
" " basalt	"	1.590	——	" 48.50
" " gabbro	"	1.620	——	" 44.08
" " harzburgite	"	1.630	——	" 42.24
Fluorite	isometric	1.434	colorless, violet, reddish	occasionally slightly birefringent
Analcite	isometric	1.487	colorless	" " "
Sodalite group:				
Sodalite	isometric	1.483–1.486	colorless, blue, green	" " "
Noselite	"	1.495	brown	
Haüynite	"	1.496		
Lazulite	"	——	blue	
Leucite	isometric	1.508–1.509	colorless	occasionally slightly birefringent; lamellar twinning frequent
Spinel group:				
Spinel	isometric	red 1.713–1.717	colorless, light red, bluish	
		blue 1.719–1.726		
Pleonaste	"		green	
Hercynite	"	1.749	"	
Gahnite	"	1.765	"	
Chromite	"	2.096	brown to yellowish red	
Picotite	"		brown	
Magnetite	"	?	opaque, black in thin sections, brown in thin films	

ISOTROPIC MINERALS (*Continued*).

Name.	System.	*n*.	Color.	Remarks.
Periclase	isometric	1.736	colorless, yellowish	
Helvite	isometric	1.739	colorless, yellowish	
Danalite	"			
Garnet group:				
Pyrope	isometric	1.741–1.750	red	
Grossularite	"	1.744–1.757	colorless, light greenish	occasionally birefringent
Common garnet	"		reddish	
Hessonite	"	1.763	brown	
Almandite	"	1.808–1.811	red, brownish red	often zonally banded
Spessartite	"	1.811	colorless, reddish	
Uvarovite	"	1.838	green	
Melanite	"	1.857	brown	often zonally banded
Demantoid	"	1.889	green	
Perovskite	isometric	2.38	grayish, brownish, greenish	occasionally birefringent
Pyrochlore group:	isometric	high		
Pyrochlore			brown, red, sometimes opaque	occasionally birefringent
Koppite	"	"	red	
Microlite	"	"	yellow, brown, red, sometimes opaque	
Pyrrhite	"	"	red to orange yellow	
Beckelite	isometric	high	light yellow	
Pyrite	isometric	?	opaque, brass-yellow by incident light	

Optically Uniaxial Minerals.

Name	System.	ω	ϵ	$\epsilon-\omega$	Opt. Char.	Color.	Pleochroism.	Remarks.
Ice	hex.	1.309	1.313	0.004	+	colorless		
Chabazite	trig.	n=1.46–1.5		0.002	∓	colorless		occasionally optically anomalous
Gmelinite	"	1.476	1.467	−0.009	∓	"		do.
		1.480	1.478	−0.002				
Hydronephelite	hex.(?)	n=	1.49	0.012	+	colorless		
Apophyllite	tetr.	1.534	1.536	0.001–0.003	±	colorless		sometimes optically anomalous
Tridymite	hex.	n=1.477		0.002		colorless		optical anomalies frequent
Quartz	trig.	1.544	1.553	0.009	+	"		
Nephelite	hex.	1.542	1.538	−0.004	−	colorless		
(eleolite)		1.547	1.542	−0.005				
Cancrinite	"	1.524	1.495	−0.029	−	color'ss, yellow, bluish, reddish		
Scapolites	tetr.				−	colorless		
$Ma-Ma_3Me_1$		1.554	1.542	−0.012				
		1.562	1.546	−0.016				
$Ma_3Me_1-Ma_1Me_2$		1.567	1.550	0.017				
		1.570	1.547	−0.023				
Ma_1Me_2-Me		1.583	1.554	−0.029				
		1.594	1.557	−0.037				
Brucite	trig.	1.559	1.579	0.020	+	colorless		
Alunite	trig.	1.572	1.592	0.020	+	colorless		
Meliphanite	tetr.	1.612	1.593	−0.019	−	yellow, reddish	weak: $O>E$	

OPTICALLY UNIAXIAL MINERALS (*Continued*).

Name.	System.	ω	ϵ	$\epsilon-\omega$	Opt. Char.	Color.	Pleochroism.	Remarks.
Eudialyte	trig.	1.608	1.610	0.002	+	colorless, yellowish, reddish	weak; $O>E$	optical anomalies frequent
Eucolite	"	1.610	1.613	0.003	+	" " "		
		1.621	1.618	−0.003	−			
Apatite	hex.	1.634	1.632	−0.002	−	colorless, gray, bluish, brown	weak; $E>O$	
		1.639	1.635	−0.004				
Melilite	tetr.	1.634	1.629	−0.005		colorless, yellowish, brown	O light yellow; E dark yellow	often indigo-blue interference color
Gehlenite		1.663	1.658	−0.005	−	colorless		isotropic in yellow light; indigo-blue interference color in white light
Fuggerite		1.691	1.691	0.000		colorless, greenish white		
Vesuvianite	tetr.	1.705	1.701	−0.004	−	colorless, brownish, greenish, bluish, reddish, yellowish	weak; $E>O$	abnormal interference colors
		1.732	1.726	−0.006	−			occasionally biaxial
		1.716	1.717	+0.001	+			
Tourmaline	trig.	1.639	1.620	−0.019	−	brown, blue, green, yellow reddish, colorless	$O>E$; strong	occasionally biaxial
		1.687	1.641	−0.046				
Xenotime	tetr.	high	high	high	+	colorless, yellowish, brownish	$E>O$; weak	
Hussakite	"	1.721	1.815	0.094	+	" " "		
Calcite	trig.	1.658	1.486	−0.172	−	colorless, grayish, yellowish, brownish		twinning lamellæ parallel to $(01\bar{1}2)$ frequent
Dolomite	"	1.682	1.503	−0.179	−	do.		no twinning lamellæ parallel to $(01\bar{1}2)$; but occasionally parallel to $(02\bar{2}1)$
		1.700	1.515	−0.185				

OPTICALLY UNIAXIAL MINERALS (*Continued*).

Na	System.	ω	ϵ	$\epsilon-\omega$	Opt. Char.	Color.	Pleochroism.	Remarks.
Magnesite	trig.	1.717	1.515	−0.202	−	colorless, grayish, yellowish, brownish		
Breunnerite	"	1.717	1.528	−0.189	−	do.		
Siderite	"	1.872	1.634	−0.238	−	do.		
		1.934	1.622	−0.312				
Corundum	trig.	1.767	1.759	−0.008	−	colorless, blue, reddish, yellow, greenish	$O>E$; O blue, E sea-green, bluish, colorless	
		1.769	1.760	−0.009				
Zircon	tetr.	1.924	1.968	0.044	+	colorless, yellowish, reddish, bluish	scarcely perceptible	
		1.931	1.993	0.062				
Cassiterite	tetr.	1.997	2.093	0.096	+	colorless, yellowish, brown, reddish		color often irregularly distributed
Anatase	tetr.	2.562	2.489	−0.073	−	colorless, yellowish, bluish	noticeable $O>E$, dark and light shades	
Rutile	"	2.616	2.903	0.287	+	yellow, reddish, violet	variable	twinning lamellæ frequent
Hematite	trig.	3.22	2.94	−0.280	−	red, brownish red; opaque, black	$O>E$	
Ilmenite	"	high	high	high		brown, opaque, black		
Pyrrhotite	hex.	—	—	—		opaque, bronze-yellow to copper red		
Graphite	hex.	—	—	—		opaque, black		

OPTICALLY BIAXIAL

Name.	System.	α	β	γ	$\gamma-\alpha$	$\gamma-\beta$	$\beta-\alpha$	Opt. Char.	Opt. Angle.	Disp.
Zeolites.										
Natrolite	ortho.	1.478 1.475	1.481 1.479	1.490 1.489	0.012 0.014	0.009 0.010	0.003 0.004	+	$2V=62°\ 15'$	$\rho<v$
Thomsonite	"	1.497	1.503	1.525	0.028	0.022	0.006	+	$2V=53°\ 50'$	strong $\rho>v$
Mordenite	monocl.	?	—	—	weak	—	—	?	large	—
Heulandite	"	1.498	1.499	1.505	0.007	0.006	0.001	+	$2V=0°$–$92°$	$\rho \gtrless v$
Brewsterite	"	—	$n=1.45$	—	0.012	—	—	+	$2V=65°$	$\rho>v$
Epistilbite [1]	"	—	1.51	—	0.010	—	—	−	$2E=70°$–$75°$	$\rho<v$
Phillipsite [1]	"	—	1.51–1.57	—	0.003	—	—	+	$2H=85°$	$\rho<v$
Harmotome [1]	"	1.503	—	1.508	0.005	—	—	+		—
Stilbite [1]	"	1.494	1.498	1.500	0.006	0.002	0.004	−	$2V=33°$	—
Laumontite [1]	"	1.513	1.524	1.525	0.012	0.001	0.011	−	$2E=54°$	strong $\rho<v$
Scolecite [1]	"	—	1.495	—	0.008	—	—	−	$2V=36°\ 26'$	—
Feldspars.										
Orthoclase [2]	pseudo-monocl.	1.518	1.522	1.524	0.006	0.002	0.004	−	$2V=69°$	$\rho \gtrless v$
Microcline [3]	tricl.	1.522	1.526	1.529	0.007	0.003	0.004	−	$2V=83°$	$\rho>v$
[illegible] [4]	pseudo-monocl.	1.521	1.525	1.525	0.004	0.000	0.004	−	$2V=0°$–$29°$	—
Soda-microcline [5]	tricl.	1.521	1.52[illegible]	1.527	0.006	0.000	0.006	−	$2V=32°$	$\rho>v$
"	"	1.525	1.531	1.531	0.006	0.000	0.006	−	$2V=43°$	—
Albite [6]	"	1.528	1.532	1.539	0.011	0.007	0.004	+	$2V=77°\ 39'$	$\rho<v$
"	"	1.532	1.533	1.539	0.007	0.006	0.001	+	$2V=81°$	—
Oligoclase [6]	"	1.534	1.538	1.542	0.008	0.004	0.004	−	—	$\rho<v$
"	"	1.539	1.543	1.547	0.008	0.004	0.004	−	$2V=88°\ 16'$	—
Andesine [6]	"	1.549	1.553	1.556	0.007	0.003	0.004	+	—	—
"	"	1.555	1.558	1.562	0.007	0.004	0.003	+	$2V=80°\ 40'$	—
Labradorite [6]	"	1.554	1.557	1.562	0.008	0.005	0.003	+	—	$\rho>v$
"	"	1.561	1.564	1.569	0.008	0.005	0.003	−	$2V=77°$	—
Anorthite [6]	"	1.575	1.583	1.588	0.013	0.005	0.008	−	$2V=77°$	$\rho>v$
Barium-orthoclase, [7] $Or_{19}Ce_1$	monocl.	1.520	1.524	1.526	0.006	0.002	0.004		$2V=71°\ 22'$	—
Hyalophane, [7] Or_4Ce_1	"	1.537	1.539	1.542	0.005	0.003	0.002		$2V=74°$	—
" Or_7Ce_3	"	1.542	1.542	1.547	0.005	0.005	0.000		$2V=78.5°$	—
Celsian, [7] Ce	"	1.584	1.589	1.594	0.010	0.005	0.005		$-2V=93°\ 38'$	—
Cordierite [8]	ortho.	1.532	1.536	1.539	0.007	0.003	0.004	−	$2V=39°$–$84°$	weak $\rho<v$
"		1.592	1.597	1.599	0.007	0.002	0.005	−	—	—
Hydrargillite	monocl.	1.535	1.535	1.558	0.023	0.023	0.000	+	$2V=0°$–$40°$	strong $\rho>v$
Aragonite	ortho.	1.530	1.682	1.686	0.156	0.004	0.152	+	$2V=18°$	weak $\rho<v$
Gypsum	monocl.	1.520	1.523	1.530	0.010	0.007	0.003	+	$2V=58°$	strong $\rho>v$
Anhydrite	ortho.	1.570	1.576	1.614	0.044	0.038	0.006	+	$2E=71°$	$\rho<v$
Mica.										
Muscovite	monocl.	1.557	1.587	1.590	0.033	0.003	0.030	−	$2V=40°$–$44°$	weak $\rho>v$
"		1.560	1.593	1.609	0.049	0.016	0.033	−	$2E=64°$–$72°$	—
Lepidolite	"	—	1.597	1.605	—	0.008	—	−	$2E=57°$–$84°$	weak $\rho \gtrless v$
Biotite	"	1.504	1.589	1.589	0.085	0.000	0.085	−	$2E=0°$–$40°$	weak $\rho \gtrless v$
"	"	1.541	—	1.574	0.033	—	—		—	—
"		1.586	—	—	—	—	—		—	—

[1] Twinning common. [2] Carlsbad twinning common. [3] Polysynthetic twinning highly exceedingly microscopic. [5] Lamellar twinning common. [7] Twinning as in orthoclase. [8] Often in

MINERALS.

Optical Orientation.	Color.	Pleochroism.
$X \parallel a$, $Y \parallel b$, $Z \parallel c$	colorless, yellowish	
$X \parallel a$, $Y \parallel c$, $Z \parallel b$	colorless	
$X \parallel b$, $Y \wedge c = 16° 30'$ in obt $\angle \beta$	"	
$Z \parallel b$, $X \parallel (001)$, or $Z \parallel b$, $X \perp (001)$	"	
$Z \parallel b$, $X \wedge c = 22°$ in obt. $\angle \beta$	"	
$Y \parallel b$, $Z \wedge c = 9°$ in obt. $\angle \beta$	"	
$X \parallel b$, $Z \wedge a = 15°$–$30°$ in obt. $\angle \beta$	"	
$Z \parallel b$, $X \wedge a = 60°$ in obt. $\angle \beta$	"	
$Y \parallel b$, $X \wedge a = 0°$–$10°$ in obt. $\angle \beta$	"	
$Y \parallel b$, $Z \wedge c = 20°$–$25°$ in acute $\angle \beta$	"	
$Z \parallel b$, $X \wedge c = 17°$ in obt. $\angle \beta$	"	
ext. on (001) = 0°; ext. on (010) = +5°, +6°	"	
ext. on (001) = +15°; ext. on (010) = +5°, +6°	"	
ext. on (001) = 0°; ext. on (010) = +5°, +6°	"	
ext. on (001) = +1°, +6°; ext. on (010) = +6°, +10°	"	
ext. on (001) = +4° 30′, +3°; ext. on (010) = +19°, +12°	"	
ext. on (001) = +2° 40′, +1°; ext. on (010) = 11° 33′, +4° 36′	"	
ext. on (001) = +1°, −5° 10′; ext. on (010) = +4° 36′, −16°	"	
ext. on (001) = −5° 10′, −17° 54′; ext. on (010) = −16°, −29° 28′	"	
ext. on (001) = −24° 56′, −37°; ext. on (010) = −32° 38′, −36°	"	
$Y \parallel b$, $X \wedge a = +2°$ in obt. $\angle \beta$	"	
$Y \parallel b$, $X \wedge a = -2°$, $-6°$ in obt. $\angle \beta$	"	
$Y \parallel b$, $X \wedge a = -18°$ in obt. $\angle \beta$	"	
$Y \parallel b$, $X \wedge a = -62°$ in obt. $\angle \beta$	"	
$X \parallel c$, $Y \parallel a$, $Z \parallel b$	colorless, bluish, yellowish	wanting or weak: $Y > Z > X$
$Y \parallel b$, $(X \parallel b)$, $Z \wedge c = 21°$ in acute $\angle \beta$	colorless	
$X \parallel c$, $Y \parallel a$, $Z \parallel b$	colorless	
$Y \parallel b$, $Z \wedge c = 52°$ in obt. $\angle \beta$	colorless	
$X \parallel c$, $Y \parallel b$, $Z \parallel a$	colorless	
$X \perp (001)$, or 5° to normal to (001), plane of opt. axes normal to (010)	colorless, greenish, yellowish	wanting or weak
like muscovite	colorless, reddish	"
$Z \parallel b$, plane of opt. axes normal to (010), anomite; $Y \parallel b$, plane of opt. axes parallel to (010), meroxene		strong: $Z > Y > \frac{X}{X}$,

developed. [4] Twinning as in orthoclase. [5] Polysynthetic twinning as in microcline, often crossed twins, and with lamellar twinning.

OPTICALLY BIAXIAL

Name.	System.	α	β	γ	$\gamma-\alpha$	$\gamma-\beta$	$\beta-\alpha$	Opt. Char.	Opt. Angle.	Disp.
Mica, continued.										
Phlogopite	monocl.	1.562	1.606	1.606	0.044	0.000	0.044	−	$2E=0°$–$40°$	$\rho<v$
Paragonite	"	very	similar	to mu	scovite			−	—	—
Zinnwaldite	"	very	similar	to bio	tite			−	—	—
Kaolinite	monocl.		$n=1.54$		0.008	app.	—	−	$2V=0°$–$90°$	—
Chlorite.										
Clinochlore	monocl.	1.585	1.586	1.595	0.010	0.009	0.001	+	$2V=51°$	$\rho>v$
Penninite [1]	"	1.576	—	1.577	0.001	(occ.0	.003)	±	$2V=0°$–$61°$	$\rho \lessgtr v$
Kammererite	"	—	—	—	—	—	—	±	$2V=0°$–$20°$	—
Corundophilite	"	—	1.583	—	—	—	—	+	$2V=46°\ 40'$	$\rho<v$
Serpentine.										
Antigorite	?monocl.	1.560	1.570	1.571	0.011	0.001	0.010	−	$2E=16°$–$98°$	$\rho>v$
"		1.490	1.502	1.511	0.021	0.009	0.012		—	—
Iddingsite		—	weak	—	str'ng	—	—	−	small	—
Chrysotile	ortho.(?)	—	$n=1.54$	—	0.013	—	—	+	$2E=16°$–$50°$	—
Talc	ortho.(?)	1.539	1.589	1.589	0.050	0.000	0.050	−	$2E=6°$–$40°$	$\rho>v$
Glauconite	(?)	—	weak	—	—	—	—	−	$2E=0°$–$40°$	—
Grandidierite	ortho.(?)	1.602	1.636	1.638	0.036	0.002	0.034	−	$2E=49°$	strong $\rho>v$
Lazulite	monocl.	1.603	1.632	1.639	0.036	0.007	0.029	−	$2E=135°$app.	$\rho<v$
Topaz	ortho.(?)	1.607	1.610	1.618	0.011	0.008	0.003	+	$2V=66°$app.	$\rho>v$
		1.629	1.631	1.637	0.008	0.006	0.002		$2V=49°\ 37'$	—
Carpholite	monocl.	$n=1.627$		—	0.022	—	—	−	$2V=60°$app.	—
Prehnite	ortho.	1.616	1.626	1.649	0.033	0.023	0.010	+	$2V=69°$	$\rho \lessgtr v$
Datolite	monocl.	1.625	1.653	1.669	0.044	0.016	0.028	−	$2V=74°$	$\rho<v$
Andalusite	ortho.	1.632	1.638	1.643	0.011	0.005	0.006	−	$2V=84°$	—
Sillimanite	"	1.660	1.661	1.682	0.022	0.021	0.001	+	$2V=20°$–$31°$	$\rho>v$
Cyanite	tricl.	1.717	1.722	1.729	0.012	0.007	0.005	−	$2V=82°$	$\rho>v$
Dumortierite [2]	ortho.	1.678	1.686	1.689	0.011	0.003	0.008	−	$2V=30°$	$\rho \gtrless v$
Amphibole.										
Anthophyllite	ortho.	1.629	1.630	1.640	0.011	0.010	0.001	±	$2Vx=90°\ 4'$	$\rho \lessgtr v$
"	"	1.633	1.642	1.657	0.024	0.015	0.009	+	$2V=96°\ 6'$	—
Gedrite	"	1.623	1.636	1.644	0.021	0.008	0.013	−	$2V=78°$	$\rho>v$
Tremolite [3]	monocl.	1.599	1.612	1.624	0.025	0.012	0.013	−	$2V=83°\ 52'$	$\rho<v$
"	"	1.607	1.623	1.634	0.027	0.011	0.016	−	$2V=80°$–$88°$	—
Actinolite [3]	"	1.600	1.616	1.628	0.028	0.012	0.016	−	$2V=80°$	$\rho<v$
"	"	1.611	1.627	1.636	0.025	0.009	0.016	−	—	—
Grünerite	"	—	$n=1.73$	—	(0.30	−0.56	)	−	$2V=50°$	—
Glaucophane [3]	"	1.621	1.638	1.639	0.018	0.001	0 017	−	$2V=42°$	—
Gastaldite	"	1.640	1.656	—	(0.01	8–0.0	24)	−	$2V=44°$	—
Pargasite [3]	"	1.613	1.620	1.632	0.019	0.012	0.007	+	$2V=52°$–$60°$	—
Common hornblende [3]	"	1.629	1.642	1.653	0.024	0.011	0.013	−	$2V=53°$–$85°$	—
" "	"	1.640	1.643	1.656	0.016	0.013	0.003	+	"	—
Soretite [3]	"	1.663	1.676	1.686	0.023	0 010	0.013	+	$2V=82°$–$90°$	—
Basaltic hornblende [3]	"	1.680	1.725	1.752	0.072	0.027	0.045	−	$2V=67°$–$80°$	—
Barkevikite [3]	"	1.687	1.707	1 708	0 021	0.001	0.020	−		
Katoforite [3]	"	—	—	—	Small		—	—	$2V$ small	$\rho>v$

[1] Abnormal interference colors frequent.

MINERALS (*Continued*).

Optical Orientation.	Color.	Pleochroism
$Y \parallel b$, plane of opt. axes parallel to (010)	colorless, yellowish, brownish	weak: $Z > Y > X$
	colorless, greenish, yellowish	wanting or weak
	colorless, yellowish, red-brown	strong: $Z > Y > X$
$Z \parallel b$, $X \wedge c = 20°$ in acute $\angle\beta$	colorless	
$Y \parallel b$, $Z \wedge c = 2°$ to $8°$ in acute $\angle\beta$	green	X, Y, green; Z, yellowish
$Y \parallel b$, Z(or X) $\wedge c = 0°$	"	" "
" "	red, violet	X, Y, violet, bluish; Z, red
	green	X, Y, green; Z, yellowish
X normal to laminæ	colorless, yellowish, greenish	wanting or faint, as in chlorite
$X \parallel a$, $Y \parallel b$, $Z \parallel c$	orange, red, brownish red	X, brownish red, orange; Y, Z, orange, yellow
$X \parallel b$, $Y \parallel a$, $Z \parallel c$.	colorless, green, yellowish	
$X \parallel c$, $Y \parallel a$, $Z \parallel b$	colorless	
	green, bluish, yellowish	wanting, or green and yellow
$X \parallel a$, $Y \parallel c$, $Z \parallel b$	blue-green	X, blue-green; Y, colorless; light bluish green
$Y \parallel b$, $X \wedge c = 9°\ 30'$ in acute $\angle\beta$	colorless, blue	X, colorless; $Y = Z$, blue
$X \parallel a$, $Y \parallel b$, $Z \parallel c$	colorless	
$X \parallel b$, $Z \wedge c = 3°$–$5°$	colorless, greenish yellow	$X = Y$, pale yellowish green; Z, colorless
$X \parallel a$, $Y \parallel b$, $Z \parallel c$	colorless	
$Y \parallel b$, $Z \wedge c = 1°$–$4°$ in acute $\angle\beta$	colorless	
$X \parallel c$, $Y \parallel b$, $Z \parallel a$	colorless reddish	X, pink; $Y = Z$, colorless to greenish
$X \parallel a$, $Y \parallel b$, $Z \parallel c$	colorless, yellowish	
X almost normal to (100), plane of opt. axes inclined 30° to (100)(010)	colorless, blue	weak: between colorless and blue
$X \parallel c$, $Y \parallel b$, $Z \parallel a$	blue, brownish, greenish, colorless	strong X, blue; Y, yellowish, violet, greenish; Z, colorless
$X \parallel a$, $Y \parallel b$, $Z \parallel c$	colorless, yellowish, brownish, greenish	X, yellowish, greenish; Y, brown, reddish; Z, yellowish, brownish
"	do.	do.
$Y \parallel b$, $Z \wedge c = 15°$, 18 in obt. $\angle\beta$	colorless	
$Y \parallel b$, $Z \wedge c = 15°$, 18° in obt. $\angle\beta$	colorless, green	X, yellowish; Y yellowish; Z, green
$Y \parallel b$, $Z \wedge c = 11°$, 15° in obt. $\angle\beta$	colorless, brown	X, colorless; Y, colorless; Z, light brown
$Y \parallel b$, $Z \wedge c = 3°$, 11° in obt. $\angle\beta$	blue, violet, yellowish green, colorless	X pale yellowish, bluish green; Y, violet; Z, blue
$Y \parallel b$, $Z \wedge c = 6°$ in obt. $\angle\beta$	do.	do
$Y \parallel b$, $Z \wedge c = 18°$, 27° in obt. $\angle\beta$	green	greens and yellows; $Z \geqslant Y > X$
$Y \parallel b$, $Z \wedge c = 12°$, 20° in obt. $\angle\beta$	green, brownish green	" " " "
$Y \parallel b$, $Z \wedge c = 17°$ in obt. $\angle\beta$	" " "	" " " "
$Y \parallel b$, $Z \wedge c = 0°$, 10° in obt $\angle\beta$	brown	browns, yellows (and greenish); $Z \geqslant Y > X$
$Y \parallel b$, $Z \wedge c = 0°$, 14° in obt. $\angle\beta$	"	do.
$Y \parallel b$, $Z \wedge c = 31°$, 58° in obt $\angle\beta$	red, brown, green	variable. $Y > Z > X$

[2] Twinning (110) [3] Twinning common

OPTICALLY BIAXIAL

Name.	System.	α	β	γ	$\gamma-\alpha$	$\gamma-\beta$	$\beta-\alpha$	Opt. Char	Opt. Angle.	Disp.
Amphibole, cont.										
Arfvedsonite [1]	monocl.	—	high	—	very	small	—		$2V$ large	—
Riebeckite	" <	1.687	—>	1.687	0.005	—	—		—	—
Crocidolite	"	—	—	—	0.025	—	—	+	$2E=90°$	—
Crossite [1]	"	—	—	—	very	small	—	−	$2V$ large	—
Hastingsite [1]	"	—	—	—	"	—	—	−	$2E=30°$–$45°$	—
Ænigmatite	tricl.	—	high	—	0.006	—	—	+	$2E=60°$ app.	$\rho<v$
Pyroxene Group.										
Enstatite	ortho.	1.656	1.659	1.665	0.009	0.006	0.003	+	$2V=70°$	$\rho<v$
Bronzite	"	1.665	1.669	1.674	0.009	0.005	0.004	+	$2V=80°$	$\rho<v$
Hypersthene	"	1.692	1.702	1.705	0.013	0.003	0.010	−	$2V=72°$–$82°$	$\rho>v$
"		1.716	—	1.727	0.011	—	—		—	—
Diopside [1]	monocl.	1.671	1.678	1.700	0.029	0.022	0.007	+	$2V=59°$	$\rho>v$
"	"	1.699	1.706	1.727	0.028	0.021	0.007	+	—	—
Hedenbergite	"	1.732	1.737	1.751	0.019	0.014	0.005	+	—	—
Augite [1]	"	1.679	1.681	1.703	0.024	0.022	0.002	+	$2V=61°$–$68°$	$\rho>v$
"	"	1.712	1.717	1.733	0.021	0.016	0.005		—	—
Ægirite-augite [1]	"	1.680	1.687	1.709	0.029	0.022	0.007	+	—	—
Ægirite [1]	"	1.763	1.799	1.813	0.050	0.014	0.036	−	$2V=62°$	$\rho>v$
Acmite	"		like	ægirite				−	—	—
Jadeite	"	—	1.654	—	0.029	—	—	+	$2V=70°$	$\rho<v$
Spodumene	"	1.651	1.669	1.677	0.026	0.008	0.018	+	—	—
"		1.660	1.666	1.676	0.016	0.010	0.006	+	$2V=54°$–$60°$	$\rho<v$
Lavenite [1]	"	—	1.750	—	0.030	—	—	−	$2V=80°$	—
Wöhlerite [1]	"	1.700	1.716	1.726	0.026	0.010	0.016	−	$2V=78°$	$\rho<v$
Rosenbuschite	"	$n=1.65$	app.	—	0.026	app.	—		$2V=90°$ app.	—
Pectolite	"	$n=1.61$		—	0.038	—	—	+	$2V=60°$	—
Wollastonite	"	1.621	1.633	1.635	0.014	0.002	0.012	−	$2V=40°$	$\rho>v$
Hjortdahlite [2]	tricl.	$n=1.69$	app.		0.012	app.	—	+	$2E$ large	—
Hainite	tricl.	$n=1.7$	app.		0.012	app.	—	+	$2E$ large	$\rho>v$
Monticellite	ortho.	1.650	1.662	1.668	0.018	0.006	0.012	−	$2V=37.5°$	$\rho>v$
Forsterite	"	—	1.659	—	high	—	—	+	$2V=86°$	$\rho<v$
Olivine	"	1.653	1.670	1.689	0.036	0.019	0.017	+	$2V=86°$–$89°$	$\rho<v$
"		1.661	1.678	1.697	0.036	0.019	0.017	+	—	—
"		—	1.692	—	—	—	—	−	$2V=89.5°$	—
Hortonolite	"	1.768	1.791	1.803	0.035	0.012	0.023	−	$2V=69°$	$\rho>v$
Fayalite	"	1.824	1.864	1.874	0.050	0.010	0.040	−	$2V=50°$	$\rho>v$
Titanolivine [2]	(?)	1.669	1.678	1.702	0.033	0.024	0.009	+	$2V=62°$	$\rho>v$
Humite [2]	ortho.	—	1.643	—	(0.028	–0.03	2)	+	$2V=68°$	$\rho>v$
Chondrodite [2]	monocl.	1.607	1.619	1.639	0.032	0.020	0.012	+	$2V=80°$	$\rho>v$
"		—	1.659	—	—	—	—	+	—	—
Clinohumite [2]	"	—	1.670	—	—	—	—	+	$2V=76.5°$	$\rho>v$
Mosandrite [4]	monocl.	1.645	1.649	1.658	0.013	0.009	0.004	+	$2V=70°$–$74°$	strong $\rho>v$
Johnstrupite	"	—	—	—	—	—	—	+	—	—
Rinkite [4]	"	1.665	1.668	—	—	—	0.003	+	$2E=78°$ app.	strong $\rho<v$
Lawsonite [1]	ortho.	1.665	1.669	1.680	0.015	0.011	0.004	+	$2V=84°$	—

[1] Twinning common. [2] Polysynthetic twinning.

MINERALS (*Continued*).

Optical Orientation.	Color.	Pleochroism.
$Y \parallel b$, $X \wedge c = 10°$, 18° in acute $\angle \beta$	blue, green-blue, lavender, violet, brownish	variable· $X > Y > Z$
$Y \parallel b$, $X \wedge c = 1°$, 8° in acute $\angle \beta$	blue, green, yellowish	X, deep blue; Y, lighter blue; Z, yellowish green
$Y \parallel b$, $X \wedge c = 18°$ 20° in acute $\angle \beta$	blue, violet, greenish	X, blue, green; Y, violet; Z, violet to colorless
$Z \parallel b$, $Y \wedge c = 20°$, 30° in obt. $\angle \beta$	blue, greenish	X, colorless, greenish yellow; Y, blue; Z, violet
$Y \parallel b$, $Z \wedge c = 24°$, 30° in obt. $\angle \beta$	blue, green	X, yellowish green; Y, deep blue-green; $Z = Y$
$Z \wedge c = 45°$ app. in obt. $\angle \beta$; plane of opt. axes nearly parallel to (010)	reddish brown	X, clear red-brown; Y, deep chestnut-brown; Z, brown-black
$X \parallel a$, $Y \parallel b$, $Z \parallel c$	colorless	
or $X \parallel b'$, $Y \parallel a'$, $Z \parallel c$	colorless, yellowish, reddish	X, yellowish: Y, yellowish: Z, greenish
"	colorless, yellowish, greenish, reddish	X, light red, brownish; Y, reddish yellow; Z, green
$Y \parallel b$, $Z \wedge c = 38° - 45°$ in obtuse $\angle \beta$	colorless, greenish	wanting
$Y \parallel b$, $Z \wedge c = 47°$ in obtuse $\angle \beta$	greenish	wanting or weak
$Y \parallel b$, $Z \wedge c = 38° - 52°$ in obtuse $\angle \beta$	pale green, brownish, reddish violet (yellowish)	wanting in paler varieties; weak in more strongly colored varieties
$Y \parallel b$, $X \wedge c = 6° - 38°$ in acute $\angle \beta$	green, yellow	X, grass-green; Y, light green; Z, yellow to brownish
$Y \parallel b$, $X \wedge c = 2° - 5°$ in acute $\angle \beta$	strong green, yellow, brown	do.
$Y \parallel b$, $X \wedge c = 5° - 6°$ in acute $\angle \beta$	brown, yellow	X, brown; Y, light brown; Z, greenish yellow
$Y \parallel b$, $Z \wedge c = 33°$	colorless	
	colorless	
$Y \parallel b$, $Z \wedge c = 23° - 26°$ in obtuse $\angle \beta$		
$Y \parallel b$, $X \wedge c = 20°$ in acute $\angle \beta$	yellow	X, pale wine-yellow; Y, yellowish; Z, orange to red-brown
$Z \parallel b$, $X \wedge c = 43°$ in acute $\angle \beta$	yellow	weak: $Z > Y = X$
$X \parallel b$, $Z \wedge c = 12° - 14°$ in acute $\angle \beta$	colorless, greenish yellow	
$Z \parallel b$, $Y \wedge c = 0°$ app.	colorless	
$Y \parallel b$, $X \wedge c = 32°$ in acute $\angle \beta$	colorless	
ext. angle $Y \wedge c$ on (001) = 25°, on (010) = 15½°	colorless, yellow	weak: $Z > Y > X$
ext. angle on (100) 0°, on (010) 4°, measured from c in plane $\perp c$ 16.5° to trace of (100)	colorless, yellow	weak: $Z > Y > X$
$X \parallel b$, $Y \parallel c$, $Z \parallel a$	colorless	
$X \parallel b$, $Y \parallel c$, $Z \parallel a$	colorless	
$X \parallel b$, $Y \parallel c$, $Z \parallel a$	colorless, yellowish, greenish	wanting
$X \parallel b$, $Y \parallel c$, $Z \parallel a$		
$X \parallel b$, $Y \parallel c$, $Z \parallel a$	yellow, greenish	
$X \parallel b$, $Y \parallel c$, $Z \parallel a$	colorless, yellowish	wanting or weak
$Z \parallel b$	yellow, red	X, red; $Y = Z$, light yellow
$X \parallel b$, $Y \parallel c$, $Z \parallel a$	colorless, yellowish	weak
$Z \parallel b$, $X \wedge c = 26° - 30°$	yellow, brownish, reddish	X, yellows; $Y = Z$, light yellow to colorless
$Z \parallel b$, $X \wedge c = 7° - 12.5°$	" " "	do.
$Y \parallel b$, $X \wedge c = 2°$	yellowish, colorless	
$Y \parallel b$	" "	
$X \parallel b$, $Y \wedge c = 7.5°$ in acute $\angle \beta$	" "	$Z > Y > X$
$X \parallel a$, $Y \parallel b$, $Z \parallel c$	colorless, light blue	wanting or weak

[3] Lamellar twinning common. [4] Twinning frequent.

OPTICALLY BIAXIAL

Name.	System.	α	β	γ	$\gamma-\alpha$	$\gamma-\beta$	$\beta-\alpha$	Opt. Char	Opt. Angle.	Disp.
Kornerupine (Prismatine)	ortho.	1.669 —	1.680 —	1.682 —	0.013 —	0.002 —	0.011 —	−	$2V=37.5°$ pr. $2E=32.5°$–$14°$ ko.	$\rho>v$ —
Axinite	tricl.	1.685	1.692	1.695	0.010	0.003	0.007	−	$2E=72°$	$\rho<v$
Astrophyllite	ortho.	1.678	1.703	1.733	0.055	0.030	0.025	+	$2E=160°$	$\rho>v$
Epidote Group.										
Zoisite [1]	ortho.	1.696	1.696	1.702	0.006	0.006	0.000	+	$2V=0°$–$60°$	strong $\rho \lessgtr v$
"	"	1.700	1.702	1.706	0.006	0.004	0.002		—	—
Thulite	"	—	—	—	—	—	—		$2V=0°$–$40°$	$\rho<v$
Clinozoisite [1]	monocl.	1.714	1.716	1.724	0.010	0.008	0.002	+	$2V=82°$–$89°$	$\rho<v$
"	"	1.724	1.729	1.734	0.010	0.005	0.005	+	—	—
Epidote	"	1.724	1.729	1.734	0.010	0.005	0.005	−	$2V=73°$–$88°$	$\rho>v$
Piedmontite	"	like epidote						(±)	$2V=89°$–$90°$	—
Allanite	"	—	1.682	—	(0.000	–0.03	2)	(+)	variable	—
Diaspore	ortho.	1.702	1.722	1.750	0.048	0.028	0.020	(+)	$2V=84°$–$85°$	$\rho<v$
Sapphirine	monocl.	1.705	1.709	1.711	0.006	0.002	0.004	(−)	$2V=69°$	$\rho<v$
Serendibite [2]	tricl.	—	1.7 app.	—	we	ak	—	(+)	$2V$ large	—
Staurolite [3]	ortho.	1.736	1.741	1.746	0.010	0.005	0.005	(+)	$2V=89°$	weak $\rho>v$
Chloritoid	monocl.	—	1.77	—	0.016	—	—	(+)	$2E=100°$–$118°$	$\rho>v$
Ottrelite	"	—	—	—	—	—	—		variable	$\rho \lessgtr v$
Sismondine	"	—	1.741	—	—	—	—		—	—
Monazite	monocl.	1.796	1.796	1.841	0.045	0.045	0.000	(+)	$2E=22°$–$36°$	$\rho<v$
Ilvaite (Lievrite) [4]	ortho.	—	1.89	—	—	—	—	(+)	$2E=60°$ and variable	—
Titanite [5]	monocl.	1.887	1.894	2.009	0.122	0.115	0.007	(+)	$2V=27°$	$\rho>v$
"		1.913	1.921	2.054	0.141	0.133	0.008		—	—
Brookite [6]	ortho.	2.583	2.586	2.741	0.158	0.155	0.003	(+)	$2E=0°$–$55°$	strong $\rho>y$
Pseudobrookite	"	—	high	—	high	—	—	(+)	$2H=84.5°$	$\rho<v$
Goethite [7]	ortho.	—	2.5app.	—	high	—	—	(−)	$2E=68°$	$r<y$

[1] Abnormal interference colors. [2] Lamellar twinning. [3] Crossed twins. [4] Transparent only in ∥ (010). [7] Axes for red

MINERALS (*Continued*).

Optical Orientation.	Color.	Pleochroism.
$X \parallel c$, $Y \parallel a$, $Z \parallel b$	colorless, yellowish	very weak
	colorless, yellowish, brownish violet	
$X \parallel b$, $Y \parallel c$, $Z \parallel a$	yellow	X, yellow, red; Y, orange; Z, lemon-yellow
$X \parallel c$, $Y \parallel b$, $Z \parallel a$, or $X \parallel b$, $Y \parallel c$, $Z \parallel a$	colorless	
	red, yellow	X, light rose to colorless; Y, deep rose; Z, yellow
$Y \parallel b$, $X \wedge c = 2°–3°$ in obtuse $\angle\beta$	colorless, reddish	weak
$Y \parallel b$, $X \wedge c = 2°–3°$ in acute $\angle\beta$	colorless, yellow green, brownish	X, colorless, yellowish, greenish; Y, yellowish green, lavender; Z, green, light yellowish brown
$Y \parallel b$, $X \wedge c = 5°–7°$ in acute $\angle\beta$	red, yellow, colorless	X, orange; Y, pink; Z, red
$Y \parallel b$, $X \wedge c = 22°–47°$ in acute $\angle\beta$	brown	$Z > Y > X$
$X \parallel c$, $Y \parallel b$, $Z \parallel a$	colorless, brownish	
$Y \parallel b$, $Z \wedge c = 8.5°$ in acute $\angle\beta$	colorless, bluish, greenish	X, colorless, light greenish blue; $Y = Z$, blue, or greenish blue $Y > Z$
	colorless, blue, greenish	strong
$X \parallel b$, $Y \parallel a$, $Z \parallel c$	yellow, reddish brown	$X = Y$, yellow; Z, red
$Y \parallel b$, $Z \wedge$ normal to $(001) = 12°$ $Y \parallel b$, $Z \wedge$ normal to $(001) = 12°$ $Y \parallel b$, $Z \wedge$ normal to $(001) = 12°$	green, blue, colorless " " " " " "	X, olive-green; Y, blue; Z, yellow-green, colorless
$X \parallel b$, $Z \wedge c = 2°–6.5°$ in acute $\angle\beta$, or $X \parallel b$, $Z \wedge c = 3°$ in obtuse $\angle\beta$	colorless, yellowish	
$X \parallel b$, $Y \parallel a$, $Z \parallel c$	brown, green	X, brown; Y, brownish yellow; Z, green
$Y \parallel b$, $Z \wedge c = 51°$ in obtuse $\angle\beta$ Z nearly $\perp$ to $X(102)$	colorless, yellowish, reddish, brownish	weak: $Z > Y > X$
$Z \parallel a$, red $X \parallel b$, $Y \parallel c$, blue $X \parallel c$, $Y \parallel b$	red, yellow, colorless	weak
$X \parallel c$, $Y \parallel b$, $Z \parallel a$	red, brownish	weak: $Y > X = Z$
$X \parallel b$, red $Y \parallel a$, $Z \parallel c$ blue $Y \parallel c$, $Z \parallel a$	yellow, brown	X, light brown; Y, yellow-brown; Z orange

thinnest sections. [5] Twinning common. [6] Axes for red and yellow $\parallel$ (001), for green and blue $\parallel$ (100), for yellow $\parallel$ (010).

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